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VARIATIONS IN THE MOISTURE CONTENT OF THE SURFACE FOOT OF A LOESS SOIL AS RELATED TO THE HYGROSCOPIC COEFFICIENT[1]

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INTRODUCTION

In this paper we report a study of the variations in moistness of the various inch sections of the surface foot of soil in some fields near Lincoln, Nebr., during seasons which were exceptionally favorable to the development of both the driest and the moistest conditions ordinarily encountered there.

The moisture content of the soil may be reported as either the total amount present, the free water—the difference between the total water and the hygroscopic coefficient, the growth water—the difference between the total water and the wilting coefficient, the latter value being computed from the moisture equivalent, the hygroscopic coefficient, or some other physical constant (*6, p. 72*)[2]—or, as in the present paper, in a form which makes evident the relative moistness of the soil, as well as all the above-mentioned values, by stating both the hygroscopic coefficient and the relation of the moisture content to this.[3] Thus, the expression 10×1.7 would indicate a total moisture content of 17.0 per cent, a wilting coefficient of 15.0,[4] 7.0 per cent of free water, and 2.0 per cent of growth water.

Variations in the moisture content of the surface soil might be expected to increase in importance with increasing humidity of climate, but even in arid regions on lands with the water table far below the surface any important changes in the moistness of the subsoil, other than reductions effected by plant roots or by percolation, appear to be almost entirely dependent upon preceding changes in the moisture content of the surface stratum of soil (*2*), which for the purposes of the present discussion we may consider to extend to a depth of 12 inches.

[1] The work reported in this paper was carried out in 1910 and 1912 at the Nebraska Agricultural Experiment Station, where the authors were, respectively, Chemist and Research Assistant in Chemistry.

[2] References made by number (italic) to "Literature cited," p. 480.

[3] ALWAY, F. J., McDOLE, G. R., and TRUMBULL, R. S. RELATION OF THE MINIMUM MOISTURE CONTENT OF THE SUBSOIL OF PRAIRIES TO THE HYGROSCOPIC COEFFICIENT. To be published in Botanical Gazette.

[4] 14.7, to be exact.

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A statement of the average moisture content of the surface foot as a whole may be very misleading. Thus, at a time when the average for the whole foot section indicates a fair amount of available moisture, the soil of the first 3 or 4 inches may be too dry to permit germination of seeds, and at another time the optimum condition may be found in the first few inches, while in the lower portion of the section the soil may be too dry to permit the penetration of roots. Therefore detailed moisture studies of the surface soil during periods of exceptionally dry weather are of special interest.

For such studies the Nebraska Experiment Station Farm at Lincoln probably provides as good a place as is to be found anywhere in the portion of the United States to be considered as strictly humid, as it lies almost as far to the west as the strictly humid climate extends on the American prairies (fig. 1).

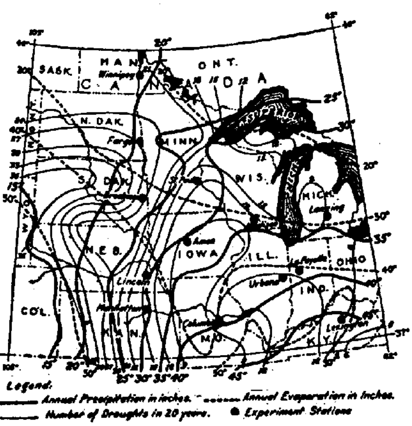

FIG. 1.—Map of a portion of the United States, showing annual precipitation,[1] evaporation from a water surface,[2] and frequency of drouths in a 20-year period, 1895–1914,[3] to indicate the especially favorable location of the Nebraska Agricultural Experiment Station for soil-moisture studies.

WEATHER CONDITIONS

From the autumn of 1906 forward we had watched at Lincoln for weather conditions that would develop a very dry surface soil, but not until late in the summer of 1909 did these appear, and then at a time when sampling could not be undertaken. They ceased just before meeting the definition of a drouth as used by the United States Weather Bureau: Thirty consecutive days between March 7 and September 30 without a total precipitation of 0.25 inch in 24 hours (7, *chart*). Then ensued a remarkably wet autumn, to be followed in turn by a record-breaking period of dry weather, which was terminated by May rains. We secured some sets of samples during this, but during the dry periods of the following year (1911) we failed to get any. Then we decided upon a detailed study of the moisture variations in the season of 1912, no matter whether it opened wet or dry, beginning the sampling as soon as the frost was out of the ground and taking samples at such times as would

[1] HENRY, A. J. CLIMATOLOGY OF THE UNITED STATES. U. S. Weather Bur. Bul. Q, pl. 26. 1906.

[2] KIMBALL, H. H. EVAPORATION OBSERVATIONS IN THE UNITED STATES. *In* Mo. Weather Rev., v. 32, no. 12, p. 558. 1904.

[3] NATIONAL WEATHER AND CROP BUL., 1915, no. 7, 4 p., 4 maps. 1915.

insure our finding the extremes occurring during the season. The maximums could be obtained after heavy rains, but in order to make sure of finding the minimums, it was necessary, whenever the soil began to get dry, to sample at frequent intervals until the next rain restored a moist condition. It happened that the season of 1912 proved almost as satisfactory for such a study as any during the 20-year period beginning with 1895.

TABLE I.—*Nitrogen and organic carbon in different inch sections of the surface foot of the different fields sampled in 1912*

NITROGEN

Depth.	Average of 5 prairie fields.	Grass field. J.	Grass field. M.	Cornfield and fallow F-C.	Exposed subsoil.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	0.347	0.403	0.237	0.237	0.047
2	.279	.258	.235	.218	.047
3	.259	.241	.235	.205	.045
4	.245	.236	.233	.200	.044
5	.234	.228	.253	.200	.044
6	.223	.227	.251	.193	.041
7	.210	.212	.239	.182	.040
8	.201	.202	.211	.173	.038
9	.193	.197	.188	.171	.038
10	.181	.190	.171	.164	.038
11	.173	.178	.164	.152	.038
12	.163	.170	.154	.142	.036
Average:					
1-3	.295	.301	.236	.220	.046
4-6	.234	.230	.246	.198	.043
7-9	.201	.204	.213	.175	.039
10-12	.172	.179	.163	.153	.037
1-6	.264	.265	.241	.209	.044
7-12	.186	.191	.188	.164	.038
1-12	.225	.228	.215	.186	.041

CARBON

Depth.	Average of 5 prairie fields.	Grass field. J.	Grass field. M.	Cornfield and fallow F-C.	Exposed subsoil.
3	3.31	2.78	2.61	2.18	0.25
8	2.39	2.27	2.27	1.92	.18
12	1.89	1.86	1.52	1.42	.18

CARBON-NITROGEN RATIO

Depth.	Average of 5 prairie fields.	Grass field. J.	Grass field. M.	Cornfield and fallow F-C.	Exposed subsoil.
3	12.8	11.6	11.2	10.6	5.6
8	11.9	11.2	10.8	11.1	4.7
12	11.6	10.9	9.7	10.0	5.0

CHARACTER OF SOIL

The soil of all the fields involved in the study is a silt loam of loessial origin, the Marshall silt loam of the Bureau of Soils of the United States Department of Agriculture the properties of which we have discussed[1] in

[1] ALWAY, F. J., McDOLE, G. R., and TRUMBULL, R. S. OP. CIT.

detail in other articles (*1,4*). In Table I there is reported the nitrogen content of the different inch sections of the fields sampled in 1912, and, for the purposes of comparison, also that of the virgin prairies in the vicinity. The samples used for analysis were composites of equal weights from all the samples on which moisture determinations had been made throughout the season; and thus, for example, from 14 borings in the case of the grass field J and from 36 in the fallow. The data on the prairies represent composites from 250 borings, 50 from each of 5 fields (*1, p. 206*). As the ratio of organic carbon to nitrogen does not change greatly in passing from the first to the twelfth inch in prairies (*1, p. 231*), or even in the ordinary cultivated fields, as may be seen from Table I, the variations in nitrogen may safely be assumed to be accompanied by corresponding variations in the content of organic matter. The low nitrogen content and low carbon nitrogen ratio characteristic of the subsoils is shown in the samples from all levels of the exposed subsoil.

TABLE II.—*Hygroscopic coefficients of the inch sections from the different fields*

Depth.	Grass field J.			Grass field M.			Corn and fallow field.					Exposed subsoil.		
	Set I.	Set II.	Average.	Set I.	Set II.	Average.	Set I.	Set II.	Set III.	Set IV.	Average.	Set I.	Set II.	Average.
Inches.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1	10.1	9.5	9.8	8.4	7.4	7.9	8.7	8.5	8.8	7.9	8.5	12.7	12.5	12.6
2	9.0	8.9	9.0	8.0	......	8.0	8.5	8.2	8.7	8.6	8.5	12.7	12.6	12.6
3	9.0	8.6	8.8	8.1	......	8.1	8.5	8.9	9.3	9.0	8.9	12.8	13.0	12.9
4	8.5	8.5	8.5	7.8	7.9	7.9	8.2	8.5	9.2	9.0	8.7	13.2	13.2	13.2
5	8.8	8.4	8.6	8.0	8.5	8.3	8.5	8.7	8.7	9.2	8.8	13.2	12.6	12.9
6	9.0	8.8	8.9	8.1	8.6	8.4	8.7	8.7	9.2	9.5	8.8	13.2	12.5	12.9
7	8.8	9.6	9.2	8.9	9.0	9.0	8.8	9.4	9.3	8.0	8.9	12.8	12.6	12.7
8	8.9	9.5	9.2	9.0	9.6	9.3	8.7	9.9	10.5	8.4	9.4	12.7	12.6	12.7
9	8.5	9.4	9.0	9.1	9.7	9.4	9.3	9.6	10.5	9.2	9.7	12.7	12.7	12.7
10	8.7	10.0	9.4	9.7	10.3	10.0	10.3	10.0	11.2	9.3	10.2	12.3	12.4	12.4
11	9.2	10.7	10.0	10.1	11.1	10.6	11.1	10.5	11.6	9.8	10.8	12.4	12.7	12.6
12	9.1	10.7	9.9	10.0	12.5	11.3	11.2	11.3	12.6	10.5	11.4	12.2	12.9	12.6
Average:														
1 to 6	9.1	8.8	9.0	8.1	......	8.1	8.5	8.6	9.0	8.7	8.7	13.0	12.7	12.9
7 to 12	8.9	10.0	9.4	9.5	10.3	9.9	9.9	10.1	11.0	9.2	10.1	12.5	12.6	12.6
1 to 12	9.0	9.4	9.2	8.8	......	9.0	9.2	9.4	10.0	9.0	9.4	12.7	12.7	12.7

No analyses were made of the samples taken in 1910, but these were from fields very similar to the grass field and fallow mentioned in Table I.

In the case of 1910 samples the hygroscopic coefficient was determined for each sample in which the moisture content was obtained, but in 1912 we confined this determination to four sets from one field and two from each of the others, each sample being a composite of two borings (Table II). While in the case of the portion of the foot section below the reach of the plow it would have been far better to have had a determination of the hygroscopic coefficient of each sample, the amount of labor involved made this prohibitive. The results from the duplicate or quadruplicate sets are sufficiently concordant to make it appear probable that in using the averages of these we introduce no serious errors. In the case of fields M and F–C, in which the surface soil through cultivation had been

kept well mixed, we might use even a single value for the first 6 sections, as we do in Table V. Even in the old grass field J and in the exposed subsoil the hygroscopicity does not vary widely from inch to inch of the lower half of the foot section.

The soils involved in this study are well represented by the Lincoln surface soil D and subsoil A, which we have used in various laboratory studies involving the movement of water (*2, p. 32; 3, p. 399*), the former being taken from various parts of the 10-acre field F-C and the latter from an adjacent excavation.

The variation in density from field to field is, as we have previously pointed out (*1, p. 224*), so great as to make data on the apparent specific gravity desirable. In June, 1912, we took from each of the fields two sets of composite samples, each from five borings, using the 4-inch plate auger mentioned below. Considerable variations in density (Table III) are shown, but scarcely sufficient to necessitate the use of different values in computing from the moisture percentages the equivalent in inches of rain. While the exposed subsoil was the most dense of all, the especially high values found for the surface inch of this are to be attributed to the beating effect of the rains. In the bluegrass pasture there was no distinct variation from level to level, except that the first inch was much the least dense. The surface layer of 6 or 7 inches in the cornfield was distinctly lighter than the lower portion of the foot section.

TABLE III.—*Apparent specific gravity of the soil at the different levels*

Depth.	Bluegrass pasture.			Cornfield.			Exposed subsoil.		
	Set I.	Set II.	Average.	Set I.	Set II.	Average.	Set I.	Set II.	Average.
Inches.									
1	0.87	0.81	0.84	1.35	1.20	1.28	1.63	1.94	1.81
2	1.17	1.19	1.18	1.09	1.07	1.08	1.42	1.38	1.40
3	1.23	1.29	1.26	1.13	1.16	1.15	1.35	1.38	1.37
4	1.22	1.28	1.25	1.18	1.02	1.10	1.33	1.44	1.41
5	1.16	1.25	1.21	1.15	1.03	1.10	1.49	1.56	1.52
6	1.16	1.21	1.19	1.09	1.11	1.10	1.32	1.51	1.42
7	1.10	1.20	1.16	1.11	1.10	1.11	1.42	1.48	1.45
8	1.16	1.24	1.20	1.14	1.29	1.22	1.40	1.52	1.45
9	1.19	1.21	1.20	1.27	1.32	1.29	1.37	1.37	1.37
10	1.21	1.22	1.22	1.32	1.35	1.33	1.32	1.39	1.36
11	1.24	1.25	1.24	1.33	1.34	1.34	1.37	1.35	1.46
12	1.24	1.25	1.24	1.36	1.34	1.35	1.25	1.42	1.34
Average	1.16	1.20	1.18	1.20	1.20	1.20	1.40	1.48	1.44

CONDITIONS DURING AN EXTREME SPRING DROUTH

WEATHER OF 1910

A striking feature of the weather of 1910 at Lincoln was the record-breaking drouth of the spring. The autumn of 1909 had been unusually wet (Table IV) and favorable for the moistening of the soil, while in

December and January the precipitation was somewhat above normal, and the ground remained frozen from December 4 until early in February, except for an occasional thaw of the surface inch or two. These conditions favored the retention of the maximum amount of moisture which the soil could hold against gravity. Then followed 94 days, January 29 to May 2, in which the total precipitation amounted to only 0.30 inch at Lincoln, and to 0.22 at the Nebraska Experiment Station, this being the driest 3-month period shown by the meteorological record for Lincoln, beginning in 1881. February was normally cold, but at the end of the month the temperature rose rapidly and during March continued high, the mean for the latter month being 16 degrees above the normal. April also was warm, with a mean of 4 degrees above the normal. The wind movement throughout this dry period was not unusually great, but during March and April the proportion of sunshine was much higher and the relative humidity of the atmosphere much lower than normal.

TABLE IV.—*Daily precipitation at the Nebraska Experiment Station from November 1, 1909, to May 31, 1910*

Day.	November.	December.	January.	February.	March.	April.	May.
1	1.25	0.75					
2		.52					0.40
3		.24	0.14				
4		.07					
5							.87
6		.12					.52
7							.21
8							
9					0.08		
10							
11	.14						
12			.52				
13	2.93	.04					
14	1.11		.02			0.01	
15							.10
16							.33
17						.04	
18							
19							
20				0.09			
21	.25						.24
22							
23							
24							
25							
26							
27							.14
28	1.57	.28					.34
29			.20				
30	.75						.15
31							
Total	8.00	2.02	.88	.09	.08	.05	3.30

The absence of precipitation after January, together with the abnormally high temperatures of March, caused an unusually early drying of the surface soil. At the end of the first week in April evidences of drouth had become very marked, and on the 9th we sampled three fields to a

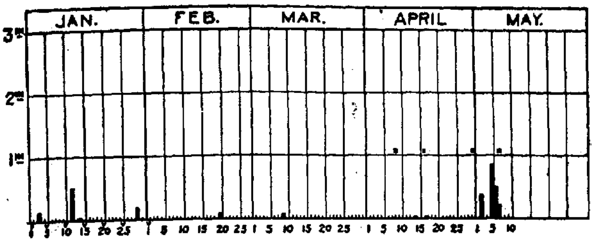

FIG. 2.—Diagram showing daily precipitation at Lincoln, Nebr., during the latter part of the record-breaking drouth of the spring of 1910. The dates of sampling are indicated by asterisks.

depth of 6 inches: a fall-plowed cornfield, a bluegrass pasture, and an alfalfa field that had been seeded in 1907. These fields were sampled weekly until the drouth was ended in May by 2 inches of rain, and once immediately after this fall, as shown in figure 2.

TABLE V.—*Moisture conditions in the surface 6 inches of soil during the spring of 1910*

Depth.	Bluegrass pasture.				Alfalfa field.				Fall-plowed field.			
	Apr. 9.	Apr. 16.	Apr. 30.	May 7.	Apr. 9.	Apr. 16.	Apr. 30.	May 7.	Apr. 9.	Apr. 16.	Apr. 28	May 7.
	MOISTURE CONTENT											
Inches.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
1	9.9	7.3	8.0	38.1	9.4	9.0	4.7	35.8	4.2	6.9	5.8	39.6
2	14.4	10.3	9.8	30.8	16.3	12.9	9.0	31.7	20.0	25.4	21.4	33.1
3	12.5	11.5	10.8	31.3	16.6	12.1	10.2	32.5	26.6	26.2	21.6	37.5
4	12.7	11.8	10.9	30.9	16.9	15.5	14.5	31.3	25.8	29.0	23.1	34.7
5	13.0	12.8	10.9	31.0	17.3	16.1	14.6	30.2	31.6	31.3	24.5	34.5
6	13.5	13.4	11.0	30.5	17.5	16.3	20.7	30.7	31.5	30.3	26.0	34.4
	HYGROSCOPIC COEFFICIENT											
1–6	9.5	9.5	9.5	9.5	9.2	9.2	9.2	9.2	10.9	10.9	10.9	10.9
	RATIO OF MOISTURE CONTENT TO HYGROSCOPIC COEFFICIENT											
1	1.0	0.8	0.8	4.0	1.0	1.0	0.5	3.9	0.4	0.6	0.5	3.6
2	1.5	1.1	1.0	3.2	1.8	1.4	1.0	3.4	1.8	2.3	2.0	3.0
3	1.3	1.2	1.1	3.3	1.8	1.3	1.1	3.5	2.4	2.4	2.0	3.4
4	1.3	1.2	1.1	3.3	1.8	1.7	1.6	3.4	2.4	2.7	2.1	3.2
5	1.4	1.3	1.1	3.3	1.9	1.8	1.6	3.3	2.9	2.9	2.2	3.2
6	1.4	1.4	1.2	3.2	1.9	1.8	2.3	3.3	2.9	2.8	2.4	3.2

MOISTURE CONDITIONS

The moisture conditions in the three fields are reported in Table V. The hygroscopic coefficients of the various inch sections of the different sets were determined, but in calculating the ratios, etc., we have used a

single value for each field—the average of all the determinations on the samples from that field—as in each field the differencess between the various samples were less than the experimental error. The samples were composites of sections from 12 cores taken 5 to 10 feet apart with a 1.5-inch soil tube.

At the time of the first sampling, the soil of the bluegrass field was already dry, showing a ratio of only 1.3 to 1.5 During the following three weeks it became steadily drier until, on April 30, the ratio had fallen to 1.1. The rains following this raised it to an average of 3.4.

Throughout the dry period the soil in the alfalfa field was distinctly moister than that in the grass field, but here also it became steadily drier until the May rains raised the ratio to an average of 3.5.

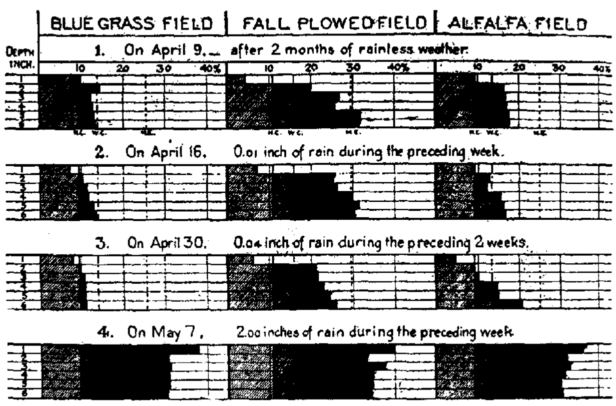

FIG. 3.—Diagram showing moisture conditions in the surface 6 inches of soil in three adjacent fields at the Nebraska Agricultural Experiment Station during and just at the close of the record-breaking drouth in the spring of 1910. The total precipitation betweeen December 4, 1909, and May 1, 1910, was as follows; December 5 to 31, 0.44 inch; January, 0.88 inch; February, 0.09 inch; March, 0.08 inch; and April, 0.05 inch.

In the fall-plowed field the moisture in the surface inch was already at the minimum on the occasion of the first sampling, the ratio being only 0.4. During the following week of dry weather it did not change appreciably, but during the next 12 days the average ratio in the 3-to-6-inch section fell to 2.2. Even then the moisture conditions below the first inch were favorable for plant growth. The May rains raised the ratio to an average of 3.2.

While the loss of moisture in the fall-plowed field was due entirely to evaporation, the uniform loss in moisture in the sections below the

second inch in the grass field indicates that the loss in it was due to transpiration, except for the slight amount lost from the first 2 inches. In the alfalfa field, with its more open stand of plants, the losses due to evaporation appear to have been greater and to have affected the soil to a greater depth.

Only in the surface inch did we find a ratio lower than 1.0. In the fall-plowed field, which had been disked in March, the surface 2 inches of soil were drier on April 9 than 19 days later.

The moisture relations are shown graphically in figure 3. The values for the wilting coefficients and moisture equivalents used in this have been computed from the hygroscopic coefficients (6, *p.* 72).

Table VI.—*Weather conditions at Lincoln, Nebr., in the season of 1912 compared with the normal*

	March.	April.	May.	June.	July.	August.
PRECIPITATION (INCHES)						
In 1912 [a]	2.06	2.23	0.69	4.03	2.68	4.15
Normal	1.23	2.77	4.25	4.32	3.83	3.71
Departure	.83	−.54	−3.56	−.29	−1.15	.44
MEAN TEMPERATURE (°F.)						
In 1912	26	53	66	68	79	75
Normal	36	51	63	72	76	74
Departure	−10	2	3	−4	3	1
SUNSHINE (PERCENTAGE OF POSSIBLE)						
In 1912	56	62	83	68	79	74
Normal	68	66	66	73	76	74
Departure	−12	−4	17	−5	3	0
WIND VELOCITY (MILES PER HOUR)						
In 1912	10	14	13	9	11	9
Normal	13	14	12	10	9	9
Departure	−3	0	1	−1	2	0
RELATIVE HUMIDITY (PER CENT)						
In 1912	80	64	58	63	61	67
Normal	70	63	68	69	67	71
Departure	10	1	−10	−6	−6	−4

[a] At University Farm.

CONDITIONS THROUGHOUT AN UNFAVORABLE SEASON

WEATHER OF SEASON OF 1912

The weather of the crop season of 1912 as a whole, as may be seen from Table VI, did not depart widely from the normal, but the practically rainless month of May with a hot wind near its close was very unfavorable for winter wheat, meadows and pastures. This dry period was, in so far as the winter wheat crop was concerned, the most severe we had an opportunity to observe during our seven years' connection with the Nebraska Experiment Station. The 30-day period, April 22 to May 31, with a total precipitation of 1.07 inches would have fallen within the definition of drouth mentioned above, except for the rain of 0.32 inch on May 4.

TABLE VII.—*Daily precipitation at the Nebraska Experiment Station from March 1 to August 31, 1912*

Day.	March.	April.	May.	June.	July.	August.
1	Trace.	0.01	0.10	0.50		
2	0.50				0.16	0.04
3	Trace.					
4			.32	.10		
5	Trace.					1.30
6		.08		Trace.		
7	.01					.04
8	.03			.30		.07
9				.21	.24	
10	.08		.15			
11	.33	.05		.06	.81	
12				.36	.05	
13	.26			2.35		.06
14	.43			.10		
15					.04	.26
16				.02		1.85
17						
18					.38	
19	Trace.					.21
20	.42	.95	.02		.25	
21		.76				
22						
23	Trace.					
24						
25		.07				
26			.10		.60	
27					.15	
28		.19				
29		.12		.03		
30						
31	Trace.					.32
Total	2.06	2.23	.69	4.03	2.68	4.15

The precipitation and temperatures of the last four months of 1911 had been more favorable than normal to the accumulation of moisture

in the soil. In the months of January and February together the precipitation amounted to 1.38 inches, compared with a mean of 1.32 inches, while the first three weeks of March were both wetter and colder than normal. The last of March was warm and dry, and by April 4 the frost was out of the ground in most fields, a little being found only in grass fields. None was met with in any of the later samplings. April did not depart much from the normal in temperature, rainfall, or wind movement.

May was very unfavorable for crops, the rainfall of 0.69 inch, occurring in five light showers (Table VII), being only one-sixth of the normal, while the latter half of the month was marked by very high temperatures, which on some days were accompanied by high winds. The most unfavorable day was the 26th, when the temperature rose to 98° F.; from

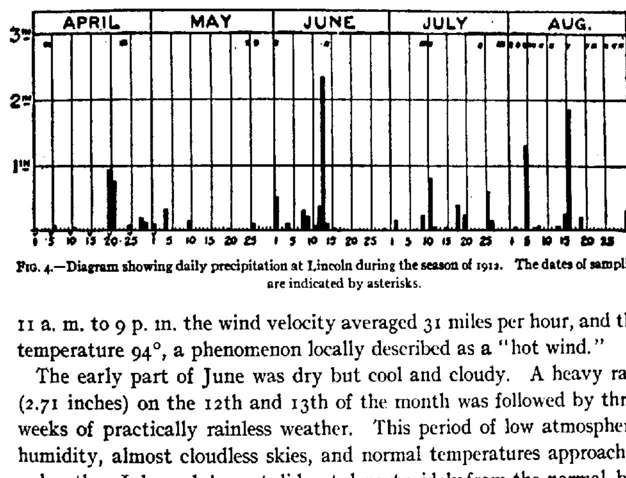

FIG. 4.—Diagram showing daily precipitation at Lincoln during the season of 1912. The dates of sampling are indicated by asterisks.

11 a. m. to 9 p. m. the wind velocity averaged 31 miles per hour, and the temperature 94°, a phenomenon locally described as a "hot wind."

The early part of June was dry but cool and cloudy. A heavy rain (2.71 inches) on the 12th and 13th of the month was followed by three weeks of practically rainless weather. This period of low atmospheric humidity, almost cloudless skies, and normal temperatures approached a drouth. July and August did not depart widely from the normal, but dry periods appeared in both months.

For the purposes of a soil-moisture study the season was exceptionally favored by the two dry periods, April 30 to May 30 and June 14 to July 11, and the two heavy rains of June 13 and August 15 and 16. The weather conditions preceding the various samplings are summarized in Table VIII. (See also fig. 4.)

FIELDS SAMPLED

All the fields sampled in this season were close together and also to the Experiment Station buildings, the most distant, M, being less than a quarter of a mile from the University Farm rain gage.

TABLE VIII.—*Weather conditions in 1912 at the Nebraska Experiment Station preceding the various samplings*

Date of sampling.		Fields sampled.[a]	Weather conditions of interval since previous sampling.
Apr.	4	J	The preceding three months had been colder than normal, with a normal amount of precipitation. Frost had disappeared, except a little within the surface, 6 inches of J. All the precipitation of March (2.06 inches) had been in the form of snow.
	5	F–C	
	23	J	Normal weather; 1.84 inches of rain since Apr. 5, 1.71 inches of this being on the 20th–21st instant.
	24	F–C	
May	25	J and F–C	Very dry month, with only 0.97 inch in seven light showers. Average temperature and wind velocity not far from normal, but with an excess of sunshine.
	27	S	0.10 inch rain on 26th.
June	1	J and F–C	A dry, hot, windy week, with a hot wind on the 26th. A rain of 0.50 inch had ended a few hours before the samples were taken.
	14	J, F, and S	A dry, cool, cloudy fortnight, ending in a rain of 2.71 inches on June 12–13.
July	9	S	An almost cloudless, rainless three-week period, with very dry atmosphere but normal temperatures.
	10	F	A shower of 0.24 inch late in the day before.
	11	F and S	In forenoon 0.81 inch of precipitation, much of it in the form of hail. Samples taken in afternoon.
	24	J	Temperatures, wind, and sunshine only slightly above normal, but rainfall only 0.72 inch, with the last (0.25 inch) on the 20th.
	29	J	0.75 inch of rain on July 26–27. Other factors normal.
	30	F and S	
Aug.	1	C and S	Normal weather. No rain.
	3	C, F, M, and S	Cool, calm, cloudy; 0.04 inch of rain on Aug. 2.
	5	M and S	Cool weather; 1.30 inch of rain earlier in the day.
	6	C, F, and M	Normal weather. No rain.
	7	C and F	Normal weather; 0.04 inch of rain.
	9	C, F, M, and S	Cool and cloudy, with 0.07 inch of rain on the 8th.
	12	C, F, and M	Normal weather. No rain.
	16	C, F, and M	Cool and cloudy, with 2.11 inches of rain during the night preceding.
	21	C and M	Weather almost normal, with 0.21 inch of rain on the 19th.
	23	C, F, and M	Temperature and wind normal, but no rain and skies almost cloudless.
	26	C, F, M, and S	A continuation of the preceding, except somewhat warmer.
	28	C, F, and M	A continuation of the preceding.
	30	F and M	Do.

[a] F=fallow field; C=cornfield; F–C=cornfield before corn plants were large enough to have an appreciable effect upon soil moisture; J and M=grass fields; S=exposed subsoil.

Field J had been in bluegrass and used as a pasture for many years. The amount and distribution of nitrogen in the first foot of this (Table I) were very similar to that in virgin prairies near by; the chief difference lay in the first inch, in which the bluegrass field showed the higher values. As this field was not under the control of the Experiment Station, and the frequent samplings were interfering with its use, it was found necessary at the end of July to abandon it. For the continuation of the study

use was made of a small part of field M, in which bluegrass had almost entirely crowded out the alfalfa sown in 1907. Previous to that year the field for almost 40 years had been in annual crops. However, the moisture data indicate that the change caused no serious break in continuity, as on August 3 the moisture conditions in field M were very similar to those in J on July 29, except for the losses from the surface few inches during the interval.

As a representative area of both fallow and corn land we employed a field lying between fields J and M and referred to below as C–F. After a long period in bluegrass it had been plowed a few years before. In 1911 it was in corn, and after the removal of the crop had been fall-plowed. In the spring of 1912 the whole of it had been planted to corn, but on June 14, in order to provide a fallow area for the study, we hoed out all the plants on a tract 6 rods square, and after this had the plot cultivated along with the rest of the field. It was kept entirely free of weeds, thus serving as a summer fallow, while the rest of the field was typical of corn land. In the latter the samples taken up to that time between the corn rows may be regarded as quite representative of fallow as well as of corn land.

The fourth area, a tract of exposed subsoil, S, lay beside a new interurban line, in preparing the grade for which the soil had been removed to a depth of 3 or 4 feet. Throughout the crop season we kept this exposed subsoil free of weeds by hoeing, but gave it no other cultivation. With each heavy shower there was a great loss from run-off, as the surface was hard and had a very gentle slope, while on the other tracts, which were almost level, there was practically none.

All the places in fields J, C–F, and S where samples were taken were sufficiently far from trees and alfalfa plants to avoid any draft upon the soil moisture by roots, but this was not the case in field M which was surrounded by alfalfa, and itself carried a few alfalfa plants.

The moisture conditions within the surface foot are shown in Tables IX to XII, while Table XIII indicates the general conditions in the underlying subsoil.

TABLE IX.—*Ratio of moisture content to hygroscopic coefficient in the surface foot of grass fields in 1912*

Depth.	April.		May.	June.		July.		August.											Extremes.	
	4	23	25	1	14	24	29	3	5	6	9	12	16	21	23	26	28	30	Maximum.	Minimum.
Inches.																				
1	4.0	4.0	0.7	3.6	4.7	1.1	2.0	1.3	4.1	3.4	2.7	1.4	4.3	3.7	2.6	1.4	1.4	1.1	[a]4.7	0.7
2	3.3	3.3	1.3	2.5	3.4	1.3	2.1	1.4	3.8	3.4	3.0	2.0	4.0	3.5	3.3	1.8	1.8	1.5	4.0	1.3
3	3.4	3.4	1.2	1.9	3.5	1.4	1.8	1.6	3.4	3.1	2.8	2.1	3.8	3.2	2.7	2.1	1.7	1.6	3.8	1.2
4	3.5	3.5	1.4	1.4	3.4	1.3	1.4	1.5	3.0	2.8	2.7	2.0	3.7	3.1	2.8	1.9	1.7	1.5	3.7	1.3
5	3.4	3.5	1.4	1.4	3.6	1.4	1.3	1.3	2.1	1.6	2.3	1.7	3.5	2.8	2.6	1.9	1.7	1.5	3.6	1.3
6	3.3	3.4	1.4	1.3	3.4	1.3	1.2	1.3	1.6	1.3	2.2	1.8	3.5	2.9	2.6	1.9	1.7	1.7	3.5	1.2
7	3.3	3.2	1.3	1.3	3.3	1.4	1.2	1.3	1.4	1.3	2.1	1.8	3.1	2.6	2.5	1.9	1.7	1.6	3.3	1.2
8	3.2	3.2	1.3	1.3	3.5	1.4	1.2	1.3	1.3	1.3	1.8	1.8	2.8	2.5	2.5	1.8	1.8	1.7	3.5	1.2
9	3.2	3.2	1.4	1.4	3.4	1.4	1.2	1.3	1.4	1.3	1.5	1.8	2.7	2.4	2.5	1.8	1.8	1.6	3.4	1.2
10	3.0	3.0	1.6	1.3	3.4	1.4	1.2	1.3	1.3	1.2	1.4	1.8	2.3	2.1	2.1	1.6	1.8	1.6	3.4	1.2
11	2.8	2.8	1.5	1.3	3.1	1.3	1.2	1.3	1.2	1.2	1.4	1.7	1.8	2.0	1.8	1.5	1.7	1.5	3.1	1.2
12	2.8	2.8	1.6	1.4	3.0	1.4	1.3	1.2	1.1	1.1	1.4	1.6	1.4	1.5	1.5	1.6	1.6	1.4	3.0	1.1
Average:																				
1–3	3.6	3.6	1.1	2.7	3.9	1.3	3.0	1.4	3.8	3.3	2.8	1.8	4.0	3.5	2.9	1.8	1.6	1.4	4.0	1.1
4–6	3.4	3.5	1.4	1.4	3.5	1.3	1.3	1.4	2.2	1.9	2.4	1.8	3.6	2.9	2.7	1.9	1.7	1.6	3.6	1.3
7–9	3.2	3.2	1.3	1.3	3.4	1.4	1.2	1.3	1.4	1.3	1.8	1.8	2.9	2.5	2.5	1.8	1.8	1.6	3.4	1.2
10–12	2.9	2.9	1.6	1.3	3.2	1.4	1.2	1.3	1.2	1.2	1.4	1.7	1.8	1.9	1.8	1.6	1.7	1.5	3.2	1.2
1–6	3.5	3.5	1.2	2.0	3.7	1.3	2.1	1.4	3.0	2.6	2.6	1.8	3.8	3.2	2.8	1.9	1.7	1.5	3.8	1.2
7–12	3.0	3.1	1.4	1.3	3.3	1.4	1.2	1.3	1.3	1.2	1.6	1.8	2.4	2.2	2.1	1.7	1.7	1.5	3.3	1.2
1–12	3.2	3.3	1.3	1.7	3.5	1.3	1.4	1.3	2.1	1.9	2.1	1.8	3.1	2.7	2.4	1.8	1.7	1.5	3.3	1.3

[a] The exceptional value of 4.7 was found on June 14 just after a very heavy rain.

TABLE X.—*Ratio of moisture content to hygroscopic coefficient in the surface foot of fallow field in 1912*

Depth.	April.		May.	June.		July.			August.										Extremes.	
	5	24	25	1	14	10	11	30	3	6	7	9	12	16	23	26	28	30	Maximum.	Minimum.
Inches.																				
1	2.7	3.6	0.5	2.6	3.9	1.8	3.4	2.1	2.7	3.6	3.5	2.2	2.0	4.0	2.4	1.7	1.9	1.3	4.0	0.5
2	3.2	3.5	1.1	2.0	3.8	1.1	3.2	2.7	2.4	3.5	3.4	2.7	2.7	3.9	2.8	2.4	2.5	2.2	3.9	1.1
3	3.2	3.4	1.8	1.3	4.0	1.6	2.9	2.8	2.4	3.4	3.4	2.9	3.0	3.9	3.0	2.7	2.6	2.6	4.0	1.3
4	3.4	3.7	2.6	1.8	4.1	2.3	3.0	3.0	2.9	3.4	3.4	3.1	3.2	3.9	3.2	3.0	2.8	2.8	4.1	1.8
5	3.5	3.6	2.4	2.7	3.7	3.0	3.2	3.1	3.0	3.5	3.4	3.1	3.1	3.9	3.5	3.2	2.9	2.8	3.9	2.4
6	3.5	3.7	2.9	3.0	3.7	3.1	3.3	3.3	3.3	3.4	3.5	3.1	3.1	3.9	3.4	3.1	3.1	3.0	3.9	2.4
7	3.5	3.5	3.0	3.0	3.8	3.2	3.3	3.2	3.3	3.2	3.3	3.2	3.2	3.7	3.3	3.1	3.0	3.0	3.8	3.0
8	3.3	3.6	2.9	3.1	3.5	3.3	3.1	2.8	3.1	2.9	3.1	2.9	2.9	3.3	3.0	2.8	2.8	2.8	3.6	2.8
9	3.1	3.2	2.8	2.9	3.4	2.9	2.8	2.7	2.8	2.9	2.9	2.8	2.8	3.1	2.9	2.7	2.7	2.6	3.4	2.6
10	2.8	2.9	2.5	2.6	3.3	2.6	2.7	2.6	2.6	2.6	2.7	2.6	2.6	2.9	2.7	2.6	2.6	2.6	3.3	2.5
11	2.6	2.7	2.4	2.5	2.9	2.5	2.5	2.5	2.6	2.4	2.5	2.5	2.5	2.7	2.6	2.5	2.5	2.5	2.9	2.4
12	2.5	2.5	2.3	2.3	2.7	2.4	2.4	2.3	2.4	2.3	2.4	...	2.4	2.6	2.4	2.4	2.4	2.4	2.7	2.3
Average:																				
1–3	3.0	3.5	1.2	1.7	3.9	1.5	3.2	2.5	2.5	3.5	3.4	2.6	2.6	3.9	2.4	2.3	2.3	2.0	3.9	1.2
4–6	3.5	3.7	2.6	2.5	3.8	2.6	3.2	3.1	3.1	3.4	3.4	3.1	3.1	3.9	3.4	3.1	2.9	2.9	3.9	2.5
7–9	3.3	3.5	2.9	3.0	3.6	3.1	3.1	2.9	3.1	3.0	3.1	3.0	3.0	3.4	3.1	2.9	2.8	2.8	3.6	2.8
10–12	2.6	2.7	2.4	2.5	3.0	2.5	2.5	2.5	2.5	2.4	2.5	2.5	2.5	2.4	2.6	2.5	2.5	2.5	3.0	2.4
1–6	3.2	3.6	1.8	2.1	3.8	2.1	3.2	2.8	2.8	3.0	3.4	2.8	2.8	3.9	2.9	2.7	2.6	2.4	3.9	1.8
7–12	2.9	3.1	2.6	2.8	3.3	2.8	2.8	2.7	2.8	2.7	2.8	2.7	2.8	2.9	2.8	2.7	2.6	2.6	3.3	2.6
1–12	3.1	3.3	2.3	2.5	3.5	2.5	3.0	2.7	2.8	3.1	3.1	2.8	2.8	3.4	2.9	2.7	2.6	2.5	3.5	2.3

TABLE XI.—*Ratio of moisture content to hygroscopic coefficient in surface foot of cornfield during August, 1912*

Depth.	August—											Extremes.	
	1	3	6	7	9	12	16	21	23	26	28	Maximum.	Minimum.
Inches.													
1	2.0	1.3	3.9	3.3	2.4	1.8	4.1	3.3	2.5	1.6	1.2	4.1	1.2
2	2.3	1.6	3.6	3.1	2.7	2.4	4.0	3.2	2.6	2.1	1.6	4.0	1.6
3	2.3	1.7	3.2	2.9	2.5	2.3	3.7	2.9	2.5	2.1	1.8	3.7	1.7
4	2.4	1.7	3.0	2.7	2.4	2.4	3.7	3.1	2.6	2.3	2.0	3.7	1.7
5	2.2	1.7	2.6	2.3	2.1	2.2	3.6	3.0	2.6	2.2	2.1	3.6	1.7
6	2.2	1.7	2.1	2.2	1.9	2.1	3.0	3.0	2.6	2.4	2.0	3.0	1.7
7	2.3	1.8	2.0	2.0	1.9	2.0	2.7	2.7	2.5	2.4	2.0	2.7	1.8
8	2.3	1.8	1.8	1.9	1.9	1.9	2.5	2.4	2.4	2.2	1.9	2.5	1.8
9	2.4	1.8	1.8	1.9	1.8	1.9	2.2	2.2	2.1	2.1	1.9	2.4	1.8
10	2.3	1.8	1.8	1.9	1.8	1.9	1.9	2.1	2.0	1.9	1.8	2.3	1.8
11	2.2	1.8	1.8	1.9	1.8	1.8	1.8	2.0	1.9	1.7	1.7	2.2	1.7
12	2.1	1.7	1.7	1.8	1.8	1.8	1.7	1.8	1.8	1.6	1.6	2.1	1.6
Average:													
1–3	2.2	1.5	3.5	3.1	2.5	2.2	3.9	3.1	2.5	1.9	1.5	3.9	1.5
4–6	2.3	1.7	2.6	2.4	2.3	2.2	3.4	3.0	2.6	2.3	2.0	3.0	1.7
7–9	2.3	1.8	1.9	1.9	1.9	1.9	2.5	2.4	2.3	2.2	1.9	2.5	1.9
10–12	2.2	1.8	1.8	1.9	1.8	1.8	1.8	2.0	1.9	1.7	1.7	2.2	1.7
1–6	2.2	1.6	3.0	2.7	2.4	2.2	3.6	3.0	2.5	2.1	1.8	3.0	1.6
7–12	2.2	1.8	1.8	1.9	1.8	1.8	2.2	2.2	2.1	1.9	1.8	2.2	1.8
1–12	2.2	1.7	2.4	2.3	2.1	2.0	2.9	2.6	2.3	2.0	1.8	2.9	1.7

TABLE XII.—*Ratio of moisture content to hygroscopic coefficient in surface foot of bare exposed subsoil in 1912*

Depth.	May.	June.	July.			August.						Extremes.	
	27	14	9	11	30	1	3	5	9	16	26	Maximum.	Minimum.
Inches.													
1	0.7	2.3	0.4	1.9	1.0	0.7	0.9	1.8	1.6	2.1	1.2	2.4	0.4
2	1.2	2.4	.6	1.6	1.6	1.4	1.2	1.9	1.8	2.2	1.8	2.4	.6
3	1.7	2.4	.9	1.4	1.6	1.7	1.6	1.7	1.8	2.0	1.9	2.4	.9
4	1.8	2.3	1.4	1.7	1.9	1.8	1.9	1.8	1.9	2.0	2.0	2.3	1.4
5	2.1	2.3	1.8	1.9	2.0	2.0	2.0	1.9	2.0	2.1	2.0	2.3	1.8
6	2.1	2.3	1.8	2.1	2.0	2.2	2.0	2.0	2.0	2.2	2.0	2.3	1.8
7	2.1	2.3	2.0	2.2	2.0	2.2	2.1	2.0	2.1	2.2	2.0	2.3	2.0
8	2.1	2.3	2.1	2.1	2.0	2.2	2.1	2.1	2.1	2.2	2.0	2.3	2.0
9	2.1	2.4	2.2	2.2	2.1	2.2	2.1	2.2	2.1	2.2	2.0	2.4	2.0
10	2.2	2.5	2.2	2.3	2.2	2.3	2.2	2.1	2.2	2.1	2.1	2.5	2.1
11	2.0	2.4	2.2	2.2	2.1	2.2	2.2	2.1	2.2	2.1	2.1	2.4	2.1
12	1.9	2.4	2.2	2.3	2.2	2.3	2.2	2.2	2.2	2.1	2.1	2.4	2.1
Average:													
1–3	1.2	2.4	.6	1.6	1.4	1.3	1.2	1.8	1.7	2.1	1.6	2.4	.6
4–6	2.0	2.3	1.7	1.9	2.0	2.0	2.0	1.9	2.0	2.1	2.0	2.3	1.7
7–9	2.1	2.3	2.1	2.2	2.0	2.2	2.1	2.1	2.1	2.2	2.0	2.3	2.0
10–12	2.0	2.4	2.2	2.3	2.2	2.3	2.2	2.1	2.2	2.1	2.1	2.4	2.0
1–6	1.6	2.3	1.1	1.7	1.7	1.6	1.6	1.8	1.9	2.1	1.8	2.3	1.1
7–12	2.0	2.3	2.1	2.2	2.1	2.2	2.2	2.1	2.1	2.1	2.0	2.3	2.1
1–12	1.8	2.3	1.6	1.9	1.9	1.9	1.9	2.0	2.0	2.1	1.9	2.3	1.8

TABLE XIII.—*Moisture conditions in subsoil of the various fields in 1912*

Depth.	Fallow.			Grass field.				Cornfield.			Exposed subsoil.			
	Hygroscopic coefficient.	Ratio. June 19.	Ratio. Aug. 29.	J. Hygroscopic coefficient.	J. Ratio June 19.	M. Hygroscopic coefficient.	M. Ratio Aug. 29.	Hygroscopic coefficient.	Ratio. July 9.	Ratio. Aug. 29.	Hygroscopic coefficient.	Ratio. June 19.	Ratio. July 9.	Ratio. Aug. 29.
Feet.														
2	14.7	1.2	1.8	14.3	1.5	14.3	1.2	13.6	1.6	1.4	11.1	2.4	2.2	2.2
3	13.5	1.6	1.8	13.6	1.5	13.6	1.2	13.7	1.7	1.4	12.1	2.4	2.2	2.2
4	13.0	1.9	1.7	13.3	1.6	13.3	1.2	13.6	1.2	1.5	11.8	2.5	2.3	2.4
5	13.0	1.9	1.8	13.3	1.9	13.3	1.2	13.5	1.7	1.9	11.0	2.6	2.3	2.4
6	[a]13.0	2.1	2.0	13.2	2.1	13.2	1.2	13.3	1.8	2.0	[a]11.0	2.7	......	2.4

[a] Datum missing. Value assumed.

The fallow, grass field J, and exposed subsoil were sampled to a depth of 6 feet on June 19, using composites of three cores taken 10 to 15 feet apart with a soil tube. On July 9 the cornfield and exposed subsoil were sampled, and on August 29 the fallow, grassfield M, cornfield, and exposed subsoil. The data on the hygroscopic coefficients of only the samples taken on July 9 and those from the fallow on August 29 are available, the other samples through an oversight being thrown out before the determinations could be made. So, in order to compute the ratios, we have in the case of three fields, F, C, and S, used the single set of coefficients on each, and in that of field M the average of those for F and C.

METHOD OF SAMPLING

The samples were obtained by means of a 4-inch plate auger with a shield, made especially for the purpose. An iron tube of 4 inches inside diameter was driven 6 inches into the ground and the auger worked inside this. It carried an adjustable 6-inch shield which could be raised 1 inch at a time and fastened by a setpin, thus automatically guarding against more than 1 inch of soil being removed without resetting the pin. The fields were sampled at two places, 10 to 20 feet apart, and the samples from the duplicate sets combined. The soil from each of the twelve 1-inch sections was placed in a covered can as soon as removed from the ground, thus preventing loss by evaporation between the time it was removed from the ground and its weighing.

EXTREMES IN MOISTNESS

The extremes in moistness were shown by the fallow and the grassfields, the cornfield occupying an intermediate position, while the exposed subsoil with its lower water-retaining capacity in comparison with

its hygroscopic coefficient, its finer texture (Table II), and its almost negligible content of organic matter (Table I), behaved quite differently from the three others.

UPPER LIMIT

At the time of the first sampling the frost was out of the plowed land and almost gone from the grass fields. Not more than a trace of rain had fallen within a 24-hour period during the 16 days preceding this, but still the ratios in both the grass field and the fallow were found almost as high as at any time later in the season, except immediately after very heavy rains, as on June 14 and August 16. In the two fields mentioned the ratios were similar, except for the drier condition of the surface inch in the fallow, and averaged alike, 3.1, for the 11-inch section (2 to 12 inches), and almost alike, 3.2 and 3.1, respectively, for the whole 12-inch section. At the second sampling, 19 days later, the ratios were almost the same, with an average of 3.3 in both fields. A rain of 1.71 inches had fallen three days before.

The heaviest rain of the season, 2.81 inches in 48 hours, fell on June 12 and 13. Samples were taken from all three fields within less than 12 hours after the cessation of this, and the highest ratios of the season found, averaging 3.7 and 3.9 for the surface 6 inches and 3.5 for the surface 12 inches of the grass field and fallow. The surface inch in the former showed the exceptionally high value of 4.7. In laboratory experiments such high ratios have been found to be common where the downward movement of the water is delayed (*2, p. 40*).

The second heaviest rain, 2.11 inches, fell during the night of August 15–16. Early in the following forenoon the uppermost 9 inches in the fallow was found as moist as on June 14, and that in the grass field almost as moist, but the lower part of the foot was distinctly drier.

In the cornfield ratios practically as high as those in the fallow were found near the surface when the sampling followed soon after a rain, as on August 5, 7, and 16, but the high ratios did not extend so far from the surface, and this for the simple reason that the corn kept withdrawing water from all levels, while in the fallow the loss was confined to evaporation through the surface, and during the month of August the rains were not sufficient to restore the moisture content of the lower sections in the cornfield to their water-retaining capacity.

On the exposed subsoil the maximum ratios were found on June 14; but even then, when the samples had been taken only a few hours after the cessation of a heavy rain, the highest ratio was 2.4 or 2.5, and the average for the 12 inches 2.3, compared with 3.5 in both fallow and grass field. While the compact, smooth, weedless surface with a gentle slope increased the run-off and prevented the ready penetration of water, this relatively low maximum, found also in laboratory experiments with similar soil (*soil A, 3, p. 402*), must be attributed to the character of the soil itself rather than to the surface conditions.

Thus the highest ratios found in the fallow and grass fields soon after heavy rains were 3.6 to 4.0 in the uppermost 6 inches and 2.9 to 3.3 in the second 6 inches, and under the influence of percolation alone these fell gradually to 2.5 to 3.0 in the lower half-foot and to a slightly higher minimum in the upper 6-inch section. In the exposed subsoil there was no difference to be observed between the upper and lower halves of the foot section, both showing a ratio of 2.3 to 2.5 soon after heavy rains, and this gradually falling to 2.1 or 2.2.

LOWER LIMIT

Marked differences, owing to the withdrawal of water through the roots in the grass and corn fields, developed during periods of dry weather, and continued even after moderate rains.

In the fallow loss of moisture could occur only through evaporation from the surface or percolation into the subsoil, with the result that there was a much greater loss from the levels near the surface. The extreme condition was shown on May 25, when the ratio in the surface inch fell to 0.5 and in the second inch to 1.1, while in the fourth it was still 2.6. The same limited depth of drying was shown during the dry periods preceding the samplings of July 10 and August 30. The persistent moistness throughout the greater portion of the surface foot in the fallow may be well brought out by considering the second 6-inch section as a whole. The ratio in this did not fall below 2.6 at any time during the five months included in the study, and on only three occasions, May 25, August 28 and 30, was it found this low. The ratio for this 6-inch section varied only between the limits of 2.6 and 3.1, except immediately after the very heavy rain of June 12–13. Even in the surface layers the ratio was in general well above that corresponding to the wilting coefficient (1.5), in the fourth inch on no occasion falling below 1.8, and in the third inch being found below 1.6 only once, on June 1. Even in the second inch it was below 2.0 for only very short periods.

There appears no reason to suspect that during the part of the year not included in the study we could have found drier soil in any of the levels than we encountered in the course of the work, which embraced the greater part of the growing season. From this it is evident that at Lincoln in fields kept in clean cultivation only rarely does the second inch of soil become too dry to permit the germination of seeds and the satisfactory growth of roots, while the fourth inch appears to remain sufficiently moist for these purposes throughout even exceptionally severe drouths.

The conditions in the cornfield were found intermediate between those in the fallow and those in the grass fields. Between June 14 and August 1 no samplings were made among the corn plants. After the plants had become large enough to make an appreciable draft upon the soil moisture,

the loss from below the first few inches was, like that in the grass field, quite uniform, as may be seen from the data for August 3 and 28; but the ratios did not fall as low, 1.7 being the minimum. Whether a severe drouth near the end of the growing season would have induced in the cornfield ratios as low as those found in the grass field earlier in the season can not be decided from the data, but it should be pointed out that in the latter part of August, when the corn was making the heaviest demands upon the soil moisture, the ratio in the lower half of the surface foot of even the grass field did not fall below 1.5, while on August 28 it was 1.8 in the cornfield, compared with 1.7 in the grass field.

On the exposed subsoil, with a smooth compact surface without a soil mulch, such as existed in the fallow, the effect of evaporation extended a little deeper, a ratio as low as 1.4 being found in the fourth inch on July 9, and ratios below 1.0 in the first three 1-inch sections. Below the fourth inch the ratios were quite uniform throughout the season from level to level, the average for the second 6-inch section varying only between 2 and 2.2, except after the heavy June rain, when it rose to 2.3. In general the ratio was 0.6 or 0.7 lower than that for the corresponding section in the fallow.

DEPTH OF PENETRATION OF RAINS

The depth of penetration of the water from different rains (Table XIV) is indicated by the distance from the surface to which the ratios were increased. In the fallow this was only roughly proportional to the amount of rain, but here the moistness of the soil below the uppermost 3-inch section was comparatively constant. Only two rains were sufficiently heavy, those of June 12–13 and August 16, to affect the twelfth inch and only the first of these two gave any evidence of having caused an addition of moisture to the second foot of soil. The low ratios found on August 29 in the levels below the first foot (Table XIII) support this conclusion. The June rain caused the passage of water into the second foot in the grass field also, but that of August 16 affected the moistness to only 10 inches. The much lesser penetration of the various rains in the exposed subsoil is to be attributed to the run-off from the smooth, hard, gently sloping surface before much of the water had time to enter the soil.

The actual addition of water to the soil of the first foot, as computed from the increase in moisture content and the relative density of the soil (Table III), amounted to nearly 90 per cent of the rainfall in the case of the grass fields, but to only about half as much in the fallow. Most of this difference must be regarded as an actual loss through run-off, as in the case of only one rain, that on June 12–13, can any part of it be attributed to a portion of the water having passed through the first into the second foot.

TABLE XIV.—*Depth of penetration and addition of moisture to the surface foot of soil*

Date of sampling.	Rain-fall.	Interval between cessation of rain and sampling.	Maximum penetration.			Water added to surface foot by the rain.		Approximate ratio in fallow before rain.	
			Fallow.	Grass field.	Exposed subsoil.	Fallow.	Grass field.	1 to 3 inches.	4 to 6 inches.
	Inches.	*Hours.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*		
July 10	0.24	24	1	......	......	......	......	1.1	2.6
June 1	.50	10	2	2 or 3	2	0.3	0.5	1.2	2.6
July 11	.81	4	6 or 7	......	2	.7	......	1.5	2.6
Aug. 5	1.30	6	6	7	3	.4	1.1	2.5	3.1
Aug. 16	2.11	6	11 or 12	10	3	.9	1.8	2.6	3.1
June 14	2.71	24	[a]12	[a]12	[a]12	1.4	2.5	1.5	2.4

[a] Rain on this occasion penetrated beyond the maximum depth of sampling: 12 inches.

The effect of a rain in increasing the moisture content of a fallowed field depends not only upon the amount of rain and the rapidity of its fall but also upon the moistness of the surface soil. Thus, an inch of rain that has fallen just slowly enough to avoid all run-off may have penetrated during the first 24 hours only 4 or 5 inches into a silt-loam soil when the initial ratio was only 0.5, whereas it would have penetrated twice as far had the initial ratio been 1.5 (*3, p. 402–403*). The half-inch rain of June 1 was held within the surface 2 inches, a comparatively dry layer in the third inch separating this upper partly moistened section from the already moist soil below (fig. 5).

LOSSES THROUGH EVAPORATION

It is evident that in the grass fields, and during August in the cornfield, the losses of water from the levels below the surface 3-inch section took place almost entirely through transpiration. In the fallow, when the ratios were as high as 2.8 to 3.3, there would be a slow downward movement of moisture into the subsoil if this were less moist until the ratio had fallen to some point between 1.9 and 2.4 (*2, p. 50*), while at the same time there would be a slow upward movement until the ratios in the sections at some little distance from the surface had fallen to about the same point. In cylinder experiments with surface soil from the fallow field it was found with two sets of 3-foot cylinders which had been filled with soil having initial ratios of 2.4 and 3.0, respectively, that at the end of 78 days the lower half of the surface foot showed ratios of 1.9 and 2.1, respectively. From other laboratory experiments it is evident that losses through evaporation from the portions of the soil 6 inches or more below the surface take place very slowly after the ratio has once been reduced to 2.0. From both laboratory experiments (*2, p. 50*) and field observation (*2, p. 63*), it is evident that the downward movement of

moisture becomes practically negligible when the ratio has been reduced to 2.0.

In the case of the fields involved in the present study, the effect of evaporation in reducing the ration below 2.0 appears to have been confined to the surface 3 inches in the fallow and exposed subsoil and to a shallower layer in the grass fields, and, during August, in the cornfield.

RELATION OF MINIMUM MOISTURE CONTENT TO WILTING COEFFICIENT AND HYGROSCOPIC COEFFICIENT

The wilting coefficient as defined by Briggs and Shantz corresponds to the ratio 1.47 (6, *p. 65*). In the cornfield during the month of August ratios lower than this were not found, although throughout the season as a whole the moisture supply of soil and subsoil together had been abnormally low, as evidenced by the yield of only 6 tons per acre of silage, and by the data in Table XII. From this it would appear that in the surface foot of cornfields at Lincoln we would rarely find growth water absent, even in seasons of drouth, and that in the case of the corn crop a statement of the amount of growth water would have more significance than that of free water. In the grass fields, on the other hand, while the free water at no time fell below about 2 per cent, the growth water was distinctly below zero on various occasions, and toward the end of July this dry condition persisted in the lower 6-inch section for at least a fortnight. The method of expressing the moisture conditions used above appears to us to have all the advantages of both of these as well as some possessed by neither.

RELATION OF MOISTURE RETENTIVENESS TO CONTENT OF ORGANIC MATTER

In both fallow and grass fields the highest ratios were observed in the surface 7 inches where the proportion of organic matter was highest, and in both these soon after heavy rains. In the eleventh- and twelfth-inch sections the maximums were below 3.0, thus approaching those in the exposed subsoil. The minimums were to be expected near the surface, but a ratio lower than 1.0 was observed only in the first inch, and this only on May 25. In the fallow the minimum ratio below the fourth inch varied between only 2.3 and 3.0, while for the different levels below the first inch in the grass fields it varied between only 1.1 and 1.3, the lower 3-inch sections showing the lowest values.

In the exposed subsoil, almost entirely lacking organic matter, the maximums were much lower. A ratio of 2.0 to 2.2 seems the highest to be expected in this after it has had a few days in which to lose by seepage the excess of water added by rain. Accordingly, ratios of 0.5 to 0.7 and 1.0 to 1.2 would indicate the proportion of growth water and free water, respectively, retained in the exposed subsoil as contrasted with 0.9 to 1.5 and 1.4 to 2.0 in the fields with an ordinary surface soil, rich in organic matter. The same results have been obtained in labora-

tory experiments already reported (No. 2, 3), but which were carried out after this field study had been concluded. The difference is shown in Table XV, compiled from the data in Tables X and XII.

TABLE XV.—*Difference in ratios shown by uncropped surface soil and exposed subsoil, from data for the 7–12-inch section*

Date.	Ratio.			Date.	Ratio.		
	Surface soil.	Subsoil.	Difference.		Surface soil.	Subsoil.	Difference.
May 25, 27	2.6	2.0	0.6	August 3	2.8	2.2	0.6
July 11	2.8	2.2	.6	9	2.7	2.1	.6
30	2.7	2.1	.6	16	2.9	2.1	.8
				26	2.7	2.0	.7

PROPORTION OF RAINFALL ACCUMULATED IN THE FALLOW

With the fallow field it is of interest to know how large a proportion of the total precipitation, 13.78 inches, which fell between the first and last samplings was accumulated in the surface soil and subsoil together. From the data in Table IX it is evident that after only three rains, those of April 20–21 (1.71 inches), June 12–14 (2.81 inches), and August 15–16 (2.11 inches), could any appreciable amount of water have penetrated beyond the twelfth inch. In the case of the last two rains the minimum amounts of water required to raise the ratios from those existing before the rain to those found immediately after must have been approximately 1.4 and 0.8 inch, respectively, thus leaving a maximum of only 4.4 inches which could have passed into the second foot. Moreover, this amount would be possible only on the assumption that there was no run-off, while the data in Table XIV indicate that with the heavy rains the loss by run-off amounted to nearly half of what fell. On all three occasions at the time of the sampling there doubtless was some water in the surface foot which would later have passed into the second foot if evaporation had been prevented, but under the conditions which prevailed it is probable that only a negligible quantity actually did so. On August 30 the first foot of soil contained the equivalent of about 0.8 inch of rain less than it did on April 5. Thus, it appears probable that out of the 13.78 inches of rain which fell during the five months less than 2 inches were accumulated in the fallow.

More frequent cultivation of the surface, with the object of maintaining a dry mulch, would probably have only reduced the amount of water accumulated, as, on one hand, moist soil would have been brought to the surface to lose its water by evaporation, and, on the other, very dry soil, with a ratio below 1.0, would have been brought next the moist layer in the fourth or fifth inch to absorb part of the free water contained in this and retain it as hygroscopic water.

DISCUSSION OF RESULTS

DISTRIBUTION OF AVAILABLE MOISTURE IN SURFACE LAYERS

After prolonged dry weather following good rains the soil without plant cover through the first few inches shows a rapid rise in moistness from the surface downward, while where there is a full stand of plants, as in the grassfields, the rise is slight and a low ratio extends beyond the twelfth inch. Where a moderate rain has fallen after the latter condition has once been established, there will be a high and comparatively uniform degree of moistness through several inches and then a sharp fall, but where very heavy rains have fallen there will be almost uniformly high ratios. These conditions are illustrated by figure 5, showing graphically part of the data from Tables IX, X, and XII.

RELATIVE IMPORTANCE OF SUCCESSIVE SOIL LEVELS AS SOURCES OF MINERAL NUTRIENTS

It is customary in making chemical studies of the soil to distinguish sharply between the 6-to-9-inch portion reached by tillage implements, called the "soil" or "surface soil," and that below, referred to as the "subsurface," or sometimes as the "subsoil." As it has been assumed that nutrients are secured through the roots mainly from the former, this has received the chief attention. As a source of nitrogen the surface layer will be much the more important because of the generally much higher content of nitrogen and the more aerobic conditions found in this.

On the soils of at least the Missouri River territory, such as represented in the present study, it is evident that a similar assumption for the mineral nutrients is not justifiable. The decline in moistness within the surface foot of the grassfields is quite uniform (Table IX), the withdrawal of water appearing as rapid in the lowest 3-inch section as in the second; and there is nothing in the data to suggest that this uniformity does not extend to a considerable distance below the twelfth inch. Almost the same remarks apply to the cornfields after the plants have made their main growth of stalk.

However, the similar readiness with which water is given up to the roots from the two levels specified does not necessarily indicate that they are equally important as sources of mineral nutrients to the crops. Aside from the fact that with annuals these are largely absorbed during the early stages of growth there is the important consideration that on nonirrigated lands the uppermost of the two sections will be in a moist condition a much greater proportion of the time, owing to many of the summer showers not being sufficiently heavy to cause any increase in moistness beyond the first few inches, as is well illustrated in the above tables. Hence, as a source of mineral nutrients the first 6 inches will be

more important than the second, although the depth of the plowline has little to do with the matter.

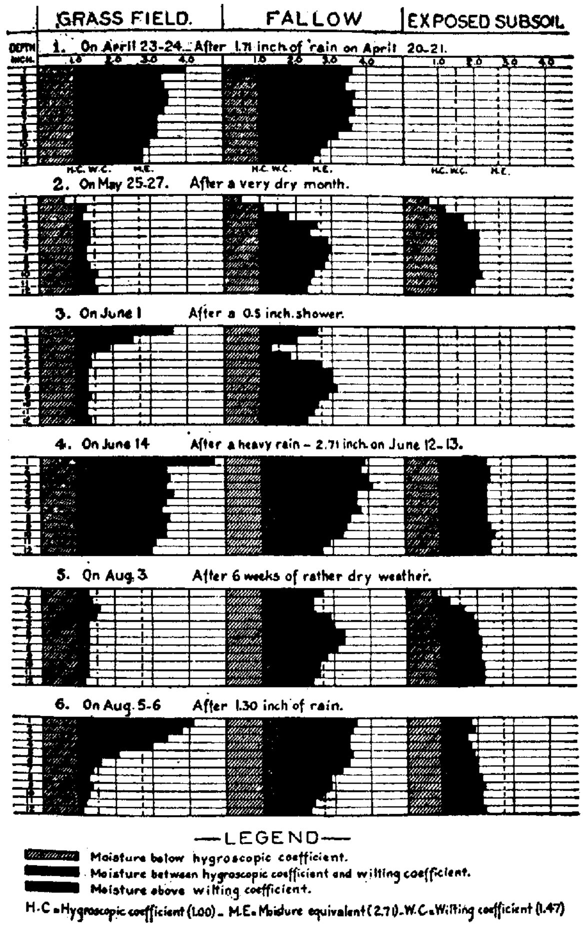

FIG. 5.—Diagram showing ratio of moisture content to hygroscopic coefficient in the surface foot of soil on three adjacent areas at the Nebraska Agricultural Experiment Station during the season of 1912. The data illustrate also the relation of the distribution of moisture to both the plant cover and the preceding weather.

Where the availability of the phosphoric acid and potash in the lower levels is distinctly less than in the plowed layer, the above remarks regarding the mineral nutrients would not apply, but with the loess soils here discussed no such difference in availability has been found (*5, p. 21*).

FREQUENCY OF DROUTHS AS AN INDEX OF THE SEVERITY OF SEASONS

The frequency of drouths as defined above is not an index of the severity of different seasons. In the 20-year period, 1895–1914, fifteen occurred at Lincoln (Table XVI), seven of these during the period of our connection with the Nebraska Agricultural Experiment Station. From the table it will be seen that the drouths so defined are especially likely to begin with the first day of March, or at least to include the greater part of that month. Of the fifteen, seven began on March 1 and two others covered a large part of that month. April is the month in which drouths are next in prominence, while May, June, July, and August have each played an important part in only a single drouth, and September in none. In so far as most crops are concerned the months of real drouth, those showing a marked deficiency in soil moisture as contrasted with a deficiency in precipitation, are June, July, and August. The dry period in May, 1912, which did not meet the above definition of drouth was far more severe on vegetation than any of the seven drouths we had an opportunity to observe. This emphasizes the failure of any single weather factor to indicate satisfactorily a deficiency of soil moisture, or to indicate a drouth in so far as crop growth is concerned.

TABLE XVI.—*Drouths*[a] *during the crop season, at Lincoln, Nebr., in the 20-year period, 1895–1914*

Series No.	Year.	Period.	Duration.	Chief month of drouth.
			Days.	
1	1895	Mar. 1 to Apr. 28	59	March and April.
2	1895	Apr. 30 to May 30	31	May.
3	1895	June 29 to July 28	30	July.
4	1899	Mar. 12 to Apr. 25	45	March and April.
5	1900	Mar. 1 to Apr. 14	45	March.
6	1902	Mar. 1 to Apr. 24	55	March and April.
7	1903	Mar. 1 to Apr. 9	40	March.
8	1906	Aug. 8 to Sept. 13	37	August.
9	1908	Mar. 6 to Apr. 16	41	March.
10	1909	Mar. 1 to Apr. 5	35	Do.
11	1909	Apr. 7 to May 11	34	April.
12	1910	Mar. 1 to May 1	62	March and April.
13	1911	Mar. 1 to Apr. 25	56	Do.
14	1911	June 8 to July 8	30	June.
15	1912	Mar. 21 to Apr. 19	30	April.

[a] Defined as a period of 30 consecutive days between Mar. 1 and Sept. 30 without a total precipitation of 0.25 inch in 24 hours (7, *chart*).

SUMMARY

The paper reports a study of the variations in moistness of the different inch sections of the surface foot of soil in some fields near the Nebraska Agricultural Experiment Station, which is near, but still within, the western limit of the strictly humid portion of the American prairies. The work was carried out during seasons which were exceptionally favorable

to the development of both the driest and the moistest conditions ordinarily encountered there, and the degree of moistness is expressed as the ratio of the water content of the soil to the hygroscopic coefficient. The soils were loessial silt loams in adjacent fields, including a clean summer fallow, a cornfield, grass fields, and an area of subsoil exposed by grading operations and kept free of vegetation.

The extremes were shown by the fallow and the grass fields. As the frost disappeared from the ground at the close of a fortnight of rainless weather the ratios in both were found as high as at any time later in the season, except immediately after very heavy rains, being alike in the two fields and averaging 3.1 to 3.2. A few hours after the cessation of a rain of 2.8 inches, ratios of 3.7 to 3.9 were found in the surface 6-inch section in both fields, but of only 2.9 to 3.3 in the second 6-inch section.

The lowest ratios in the portions of the foot section below the immediate surface were found in the grass fields, where, during dry periods, they fell as low as 1.2, the twelfth inch becoming as dry, and this as quickly, as the overlying levels, evidence that the chief loss of water was through transpiration. In the cornfield as the plants approached maturity the moisture was withdrawn uniformly from the different levels but the ratios did not fall below 1.5.

In the fallow the soil at only a few inches from the surface remained moist throughout the driest periods. In the second 6-inch section the ratio did not fall below 2.6, varying during the season only between the limits 2.6 and 3.1. Even in the fourth inch the ratio did not fall below 1.8, while in the second it was below 2.0 for only very short periods.

In the grass fields after the ratios had been reduced to a low point only rains amounting to 2.0 inches or more were able to penetrate to a depth of 12 inches, the water from lighter rains being held within the surface foot until it was transpired by the plants or evaporated from the surface. In the fallow with its moist soil the penetration was not much greater, but this is to be attributed to the rain falling more rapidly than it could be absorbed or retained on the plant free surface.

In the grass fields, and in the cornfield after the plants were well grown, the moisture was lost chiefly through transpiration, while on the fallow and exposed subsoil it was lost through evaporation and run-off, but little of the rainfall of the five months covered by the study reaching the second foot. In the grass field doubtless practically all the 13.8 inches that fell were so returned to the atmosphere, while in the fallow probably less than the equivalent of 2.0 inches of rain was accumulated in surface soil and subsoil together.

The exposed subsoil kept free of vegetation differed markedly from the fallow with ordinary surface soil, the maximum ratio being only 2.4 to 2.5 and in the second 6-inch section the ratio during the season varied only between 2.0 and 2.3. The differences in the maximum ratio between the first and the second 6-inch sections in the fields with ordinary surface

soil and the much greater difference between the ratios in the surface layers of these and those in the exposed subsoil appear at least partly due to the differences in the proportion of organic matter.

Under the climatic conditions of the locality more significance is to be attached to a statement of the amount of growth water than that of the free water in the case of corn, while the reverse holds true for grass fields, but neither of these is as satisfactory as a statement of the hygroscopic coefficient, together with the ratio of the moisture content to this.

The distribution of free water in the surface foot assumes characteristic forms, dependent upon the preceding weather conditions and the presence of a plant cover.

The moisture relations indicate that as a source of mineral nutrients the upper half of the surface foot may be more important than the lower, but this is due to the depth of penetration of rains and not to the depth of the plowline, nor to the distribution of the roots.

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SUBSOILING, DEEP TILLING, AND SOIL DYNAMITING IN THE GREAT PLAINS[1]

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GENERAL DISCUSSION OF SUBSOILING, DEEP TILLING, AND SOIL DYNAMITING

There is perhaps no agricultural operation that is so often and enthusiastically advocated and at the same time so little practiced as that of loosening or tilling the soil below the depth reached by the ordinary plow.

The supposed necessity or desirability of such an operation appears to be based on a widespread belief that only that part of the soil loosened and moved by man with his implements of tillage is utilized by nature in the production of crops; that this part of the soil is the only part that participates in the storage of water to be recovered by the crop; that the development and growth of the roots of crop plants is limited to this portion of the soil, and that this is the only portion of the soil from which plant food may be obtained by the crop.

A less extreme belief recognizes that these things are not entirely limited to the portion of the soil that man loosens, stirs, pulverizes, or inverts, but holds that the soil so treated provides a more effective medium for their action than does the undisturbed soil.

Such beliefs apparently either overlook the luxuriant vegetation produced on land that has never known the tillage implements of man or assume that the roots of crop plants are essentially different in their relation to the soil than those of other plants or of the same plants growing wild.

Studies of the root systems of agricultural crops have shown that in the deep soils and subsoils of the prairies and plains the roots of annual crops are well distributed through the soil to a depth of 3 feet or more.

[1] The experimental work of this investigation was carried out at 12 field stations of the Office of Dry-Land Agriculture Investigations. The following members of the scientific staff of the office assisted in the experiments at their stations: J. M. Stephens, superintendent, Judith Basin Substation, Moccasin, Mont., in charge of northern district; O. J. Grace, superintendent, Akron (Colo.) Field Station, in charge of central district; E. F. Chilcott, superintendent, Woodward (Okla.) Field Station, in charge of southern district; W. P. Baird, assistant, Judith Basin Substation; A. E. Seamans, assistant, Huntley (Mont.) Field Station; W. A. Peterson, superintendent, F. E. Cobb and N. O. Henchel, assistant arboriculturists, Max Pfaender, assistant in horticulture, J. T. Sarvis, physiologist, and R. S. Towle, assistant, Mandan (N. Dak.) Field Station; O. R. Mathews, assistant, Bellefourche (S. Dak.) Field Station; F. L. Kelso, superintendent, Ardmore (S. Dak.) Field Station; Albert Osenbrug, assistant, Scottsbluff (Nebr.) Field Station; W. E. Lyness, assistant, Archer (Wyo.) Field Station; J. F. Brandon, assistant, Akron (Colo.) Field Station; A. L. Hallsted, assistant, Hays (Kans.) Substation; C. B. Brown, assistant, Garden City (Kans.) Substation; L. N. Jensen, assistant, Amarillo (Tex.) Field Station; H. G. Smith, superintendent, Tucumcari (N. Mex.) Field Station.

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If the water stored within the zone of normal root development is not sufficient to meet the needs of the crop, the roots will continue during the life of the plants to penetrate deeper, provided the soil below is wet. Under such conditions the roots may successively occupy the fourth, fifth, and sixth foot. The roots of winter wheat have been traced to a depth of 8 feet. In this connection it should be noted that fertility of the subsoil is a general characteristic of the soils of semiarid regions. Roots do not penetrate dry soil, even though there may be wet soil beneath it. Where shallowness of soil restricts root development to a depth less than normal, the plants may attain complete development, provided the water content of the zone occupied by the roots is maintained above the limit of availability. The shallower the soil or the smaller the quantity of available water it can retain the more dependent is the crop on rains that fall while it is growing.

All field studies of root systems have been made on land given ordinary plowing, generally to a depth of about 6 inches. No comparative studies of root systems as developed in deep and in shallow plowing have been made. But studies that have been made on the quantity of water stored in the soil, the depth to which it is stored, the depth from which it is used and the degree to which it is exhausted, and the behavior and yield of the crop on land tilled to different depths all afford an abundance of indirect evidence that the form and extent of root systems are not primarily affected by the depth of tillage.

Extensive soil-moisture studies that have been made in connection with the investigations reported in this paper indicate that the ability of the soil to take in or to retain water, or to give up water to the crop, is not determined by the depth of tillage. Sands and light sandy soils offer little resistance to the entry and downward passage of water. They are little changed and certainly not improved in this respect by cultivation. With the heavier clay soils in which penetration is slower and more difficult it would seem that there was more opportunity for improvement by a mechanical loosening. The result is not, however, what it might at first thought appear to be. The mechanical loosening that may be affected when such soils are dry enough to be loosened by tilling is of no consequence so long as the soil remains dry. When rains come and water enters the soil, it carries soil material with it in its downward passage through the loosened soil. The clay expands on becoming wet and the loosened and wetted area becomes an amorphous mass. On drying, the soil contracts. A part of the shrinkage is downward, and a part of it is lateral. The lateral shrinkage results in cracks that may open the soil as effectively as any tillage operation. Mathews (*3*)[1] has shown that when allowed opportunity for free expansion a soil when wet may occupy 2½ times the volume it did when dry.

[1] Reference is made by number (italic) to "Literature cited," p. 521.

One cycle of wetting and drying overcomes the effect of cultivation. As Mosier and Gustafson (*4*) say—

> The subsoil ran together as soon as it was wet and became approximately as it was before.

It is frequently stated that deep tillage prevents run-off by facilitating penetration. Soil-moisture studies show that in the Great Plains penetration and run-off are determined more by the condition of the immediate surface than by the depth to which the soil has been cultivated. Run-off in the Great Plains other than that from the rapid melting of snow on frozen ground is from torrential rains in which the precipitation of a few minutes or hours is measured in inches. Beating rains of this character smooth and compact the surface so that the run-off is heavy. As the great volume of water that constitutes the run-off does not get beneath the surface, the condition of the subsoil is of no importance in determining its amount. The finer and smoother the surface has been made by cultivation the more easily and quickly is it reduced to a condition that resists penetration and facilitates run-off. The Akron, Colorado, soil, on which the results of subsoiling have been especially unfavorable to the practice, is a good example of a soil from which there often may be heavy run-off from a smooth and compacted surface overlying a very loose and open subsoil.

Many cases have been noted in the course of these experiments where the amount of water that entered the soil from a heavy rain was greater on a dry, cracked stubble than on a plowed field.

Under the semiarid conditions of the Great Plains, where production is determined by the quantity of water available to the crop, the amount of water that enters and is retained by the soil is not determined by the depth of cultivation, and consequently is not increased by an increase in such depth. Under more humid conditions, where rainfall is sufficient to fill the soil regardless of the amount that may be lost by run-off, the depth of cultivation can not add to the amount retained and so can not be a determining factor, in so far as this item is concerned.

It must be recognized, however, that the possible combinations of conditions of looseness, fineness, and water content of subsoil and surface and the character and amount of rainfall are so many that they are seldom exactly duplicated, particularly in semiarid regions. Different combinations of these factors may give rise to different results, as is clearly shown both in soil-moisture studies and in the crop yields reported in this paper. The study of root systems and of soil moisture indicates that the effect or lack of effect of differences in the depth of tillage is accurately measured by crop yields. From the average yields obtained it may be safely assumed that under the soil and climatic conditions obtaining in the region where the experiments were conducted a combination of factors favorable to deep tillage does not occur often enough nor result in increases great enough to warrant its general practice.

It is mistaking or failing to recognize the purpose of plowing that leads to the belief that its efficiency increases with its depth even though that depth be extended below all practical limits of cost and effort. Plowing does not increase the water-holding capacity of the soil, nor the area in which roots may develop or from which the plants may obtain food. Plowing removes from the surface either green or dry material that may encumber it, provides a surface in which planting implements may cover the seed, and removes or delays the competition of weeds or plants other than those intended to grow, and in some cases by loosening and roughening the immediate surface checks the run-off of rain water. All these objects are accomplished as well by plowing to ordinary depths as by subsoiling, dynamiting, or deep tilling by any other method. There is little basis, therefore, for the expectation of increased yields from these practices, and the results of the experiments show that they have been generally ineffective.

EXPERIMENTS WITH SUBSOILING IN THE GREAT PLAINS

There are here reported results of subsoiling at 12 stations of this office in the Great Plains area for a total of 66 station-years, or an average of 5½ years at each station. From four to seven crops have been grown each year at each station. The crops under trial have been spring wheat, winter wheat (*Triticum aestivum*), oats (*Avena sativa*), barley (*Hordeum* spp.), flax (*Linum usitatissimum*), corn (*Zea mays*), kafir, milo, broom corn, sorghum (*Audropogon sorghum*), and cotton (*Gossypium* spp.), as shown in the results from the individual stations.

The length of time covered and the wide range of climatic conditions encountered in these experiments make the results representative of the widest range of conditions likely to be experienced in the region.

Figure 1 is a map of the Great Plains, showing the location of the field stations at which experiments have been conducted.

METHOD OF WORK

The results with subsoiling are all from continuous cropping of land to the crop under study. In this series of continuously cropped plots there are in general five methods under trial: Spring plowing, fall plowing, alternate cropping and summer tilling, subsoiling, and listing. In this study the results from the subsoiled plots, which are designated in the fields and notes as the "E plots," are compared with those from the fall-plowed plots, known as the "B plots." Except for the subsoiling practiced on E, these plots are treated exactly the same. They are plowed as early in the fall as is practicable after the crop has been removed. The plots are plowed to a good depth, the standard being set at 8 inches.

In addition to the plowing of plot E, a subsoiler is run in the bottom of the furrow, loosening the soil to a further depth of 6 to 8 inches,

or to a total depth of 14 to 16 inches. The variation from this depth is hardly more than 2 inches either way. In general, subsoiling is done for two years in succession, and then is omitted for two years. The present outline calls for subsoiling at all stations in the fall of 1915, 1918, and 1919. The ground may be worked down in the fall or left rough over the winter. In the early years of the work these plots were harrowed immediately after plowing and kept cultivated during the fall, but the tendency has been more and more to leave them rough over the winter. This is considered the better practice both for catching snow and preventing run-off and soil blowing, and at the same time it reduces the expense of crop production.

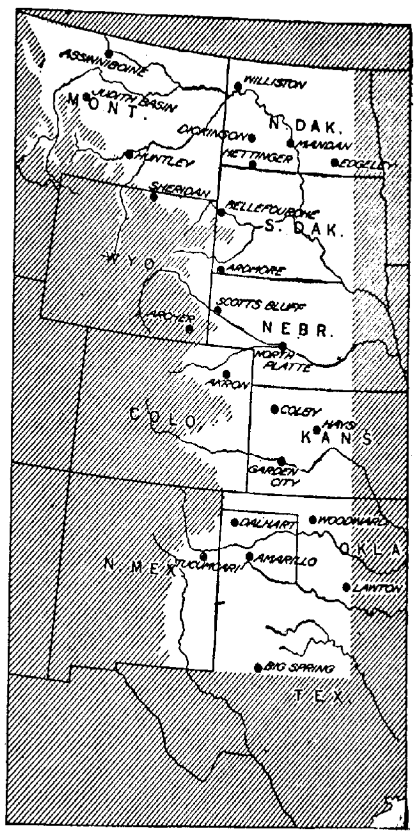

FIG. 1.—Map of the Great Plains area, which includes parts of 10 States and consists of about 400,000 square miles of territory. Its western boundary is indicated by a 5,000-foot contour. The location of each field station within the area is shown by a dot within a circle (⊙).

In some cases where it has been impossible to plow as early as desired, the stubble has been disked and the plowing done later.

In the spring the ground is finally prepared for seeding by the necessary use of the disk or smoothing harrow, or both.

Seeding is done with standard farm machinery at what is believed to be the best date and rate per acre.

The plots are 2 by 8 rods, or 0.1 acre in size. The B and E plots of any one crop are separated on their long dimension by the C and D plots, or an interval of 78 feet. The different crops may be more widely separated, but all are within a field of approximately 20 acres at each station.

METHOD OF STUDY AND PRESENTATION OF RESULTS

Tables I to XII, inclusive, present in a separate table for each field station the yields of each crop each year on plot B (not subsoiled) and on plot E (subsoiled). The average yield of each plot for the entire period of years is also presented. The principal comparisons have been made and the conclusions of the effects of subsoiling drawn from the annual and average yields. But in order to obtain a uniform expression of difference on which to calculate the probable error of the results, and through which to compare the relative effect upon different crops and at the several stations, it has seemed necessary to express the differences in some form of ratio or percentage.

A thorough study of the data has been made by means of percentages calculated on four different bases. The ratios of the average yields have been computed for each crop at each station by dividing the average yield of plot E by the average yield of plot B. This single calculation does not afford either an expression of the results each year or opportunity for the determination of the probable error based on annual differences.

In each experimental field there are a large number of plots of each crop grown each year by various methods. The difference in yield between B and E each year has been calculated as a percentage of the average yield of all plots of the same crop in the field for that year. Objection has been made to the use of this method for this particular study, for the reason that with some crops the yields of these methods are below the general average and with other crops they are above it. This results in some cases in a disproportionate valuation of the entity under study. The average departure of the results as calculated by this method from those obtained by the first method is so high as to make its use for the present study unsatisfactory.

The difference in yield between plots B and E each year has been calculated as a percentage of the yield of B, which may be considered as the control plot, or the one giving the yield that it is sought to increase on E by means of subsoiling. For the results in hand this method gives undue weight to comparatively small differences in yield as the yield of the plot selected as the base of comparison approaches zero. There are so many of these cases that the results of comparison by this method are not satisfactory when compared with actual differences in average yield.

This objectionable weighting of small differences in yield is largely overcome and the results smoothed by using the arithmetic mean of the yield of the two plots under study as the base on which to calculate the difference between the two as a percentage. This method tends, however, to reduce the percentage when it is above and to increase it when it is below 100. In over half the comparisons the ratios depart from 100 by less than 10, and within this range the distortion is not great. The average results are further made up of varying combinations of increases

and decreases, so this method is more satisfactory in the averages as determined by it than might at first be thought possible. It is this method that has been adopted for presentation. With each pair of comparable yields in Tables I to XII is given the percentage of the yield of plot E to the mean of the yield of B and E. These percentages are averaged at the right, and the probable error of this average is given. In Table XIII these average ratios and probable errors are assembled and further averaged by crops and by stations. The data in this table are presented graphically in figures 2 and 3.

In these tables and charts a percentage of 100 shows that there was no difference in the yield of the two plots, a percentage above 100 shows that the higher yield was from the subsoiled plot, and a percentage below 100 shows that the higher yield was produced on the plot not subsoiled.

It is recognized that the use of ratios weights the results, and that averages of such ratios are not the same as the ratios of the averages. They are not, therefore, accurate quantitative expressions of the results and are not a measure of the economic value of a method as compared with a control. They are not, however, in the present study misleading in direction, and serve a useful purpose of facilitating comparisons between things otherwise difficult of direct comparison.

JUDITH BASIN FIELD STATION

The field station at Moccasin, Mont., in the Judith Basin, is located on a heavy clay soil of limestone origin. The soil is apparently very rich in available fertility. It is underlain at a depth of approximately 3 feet with a limestone gravel that is closely cemented with lime materials. The gravel subsoil, which extends to a depth of about 30 feet, is practically free from soil. While it is so closely cemented that it does not unduly drain the soil, it is not of a character to allow the storage of available water or the development of roots within it.

Comparative results of fall plowing and of subsoiling are available for spring wheat, winter wheat, oats, barley, corn, and flax for the seven years 1910 to 1916, inclusive. Crops were raised on this land in 1908 and 1909, but the first subsoiling was not done until the fall of 1909. Hail in 1912 destroyed all crops except winter wheat and flax. The yields of these crops were considerably reduced by the storm, but as the damage was relatively the same on each plot, the yields are used. The winter wheat crop of 1916 was lost by winterkilling.

The E plot for each of the crops was subsoiled in the fall of 1909, 1910, 1911, 1913, and 1915.

The yields and the ratios as previously described are presented in Table I. None of the average differences observed are significant, the departures from the mean being very small and either less or only slightly greater than their probable errors. This is true of all crops except barley, which, from the results at this station alone, would appear to be

peculiarly benefited by subsoiling. This is a point not supported by the evidence of the 10 other stations at which barley is grown and therefore must be attributed to a soil difference which has been observed and to damage by gophers to the B plot in at least two seasons. While this damage has been noted in the field, it has not been taken into account in the tables. The year of 1913 is the only year in the series when all crops yielded as much, or more, on the subsoiled plot as they did on the ordinary plowed one. While it is probable that the relation is only a coincidence, it is worthy of note that no subsoiling was done in the fall of 1912 in preparation for this crop. The average results of all crops, including barley, at this station is only 103, with a probable error of 1. The conclusion is that subsoiling has been without practical effect.

TABLE I.—*Yields at the Judith Basin Field Station, Moccasin, Mont., of spring wheat, winter wheat, oats, barley, corn, and flax each year from 1910 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of corn are expressed in pounds of stover per acre; of other crops in bushels of grain per acre]

Crop and plot.	Yield or ratio.								Probable error of mean ratio.
	1910	1911	1912	1913	1914	1915	1916	Average.	
Spring wheat:									
Plot B	14.0	22.0	(a)	18.5	15.8	27.0	21.1	19.7	......
Plot E	15.0	23.5	(a)	22.8	16.5	25.5	20.0	20.6	......
Ratio of E to mean	103	103	......	110	102	97	97	102	±1.3
Winter wheat:									
Plot B	24.0	23.5	12.2	23.2	16.3	28.5	0.0	18.2	......
Plot E	23.2	22.4	12.5	26.2	15.5	28.3	0.0	18.3	......
Ratio of E to mean	98	98	101	106	97	100	......	100	±0.9
Oats:									
Plot B	20.9	51.5	(a)	65.0	49.3	50.6	45.6	47.2	......
Plot E	25.3	53.0	(a)	65.0	40.6	57.1	43.1	47.4	......
Ratio of E to mean	110	101	......	100	90	106	97	101	±1.9
Barley:									
Plot B	12.5	24.1	(a)	21.9	18.1	24.0	20.5	20.2	......
Plot E	15.0	32.6	(a)	32.9	23.5	25.8	20.5	25.1	......
Ratio of E to mean	109	115	......	120	113	104	100	110	±2.2
Corn:									
Plot B	2,900	7,000	(a)	4,000	3,700	8,450	6,200	5,375	......
Plot E	3,650	4,780	(a)	5,800	5,000	8,000	6,200	5,572	......
Ratio of E to mean	111	81	......	118	115	97	100	104	±4.2
Flax:									
Plot B	6.2	13.2	5.4	12.9	9.1	16.0	10.3	10.4	......
Plot E	6.5	14.1	4.9	13.2	10.7	17.3	10.3	11.0	......
Ratio of E to mean	102	103	95	101	108	104	100	102	±0.9

[a] Crop destroyed by hail.

HUNTLEY FIELD STATION

The field station at Huntley, Mont., is located in the valley of the Yellowstone River at the foot of the first bench. The soil is a heavy gumbo clay to the depth of about 8 feet. Underlying the soil is a considerable depth of free-drained gravel.

Table II presents the yields and ratios of four years for spring wheat, oats, flax, and corn, and three years for winter wheat at this station. The only consistent results to be noted either by years or by crops are that the corn and winter-wheat crops each year have been the heavier on the subsoiled plot, while with flax the reverse has been true. The differences, however, are not enough greater than the probable error to make them significant, particularly when considered in connection with similar comparisons of the same crops at other stations.

TABLE II.—*Yields at the Huntley (Mont.) Field Station of spring wheat, winter wheat, oats, corn, and flax each year from 1913 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Croop and plot.	Yield or ratio.					
	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:						
Plot B	11.8	20.2	25.3	7.8	16.3	
Plot E	14.5	17.5	25.5	6.2	15.9	
Ratio of E to mean	110	93	100	89	98	±3.4
Winter wheat:						
Plot B		25.7	13.3	12.7	17.2	
Plot E		27.8	13.6	15.5	19.0	
Ratio of E to mean		104	101	110	105	±2.0
Oats:						
Plot B	34.0	48.4	56.9	17.8	39.3	
Plot E	39.3	52.8	61.9	16.9	42.7	
Ratio of E to mean	107	104	104	97	103	±1.5
Corn:						
Plot B	14.8	13.2	40.6	25.4	23.5	
Plot E	25.7	13.9	42.5	29.6	27.9	
Ratio of E to mean	127	103	102	108	110	±4.1
Flax:						
Plot B	12.5	8.4	16.7	5.4	10.8	
Plot E	11.9	4.7	13.4	4.5	8.6	
Ratio of E to mean	98	72	89	91	88	±3.7

MANDAN FIELD STATION

The record for the Mandan (N. Dak.) Field Station covers only two years, but spring wheat has been replicated four times each year and all other crops, except flax, three times each year. On the main field the soil is a light, sandy loam with a more sandy subsoil. On this field spring wheat appears twice and the other crops once. The soil of the south field is a heavy clay loam with a heavier subsoil. All crops except flax are grown in duplicate on the south field.

TABLE III.—*Yields at the Mandan (N. Dak.) Field Station of spring wheat, oats, barley, corn, and flax for 1915 and 1916 on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the two years; the ratio of the yield on E to the mean of the yield on B and E each year and replication, the mean ratio, and the probable error of the mean ratio*

[Yields in bushels per acre. Flax one, spring wheat four, and other crops three replications each year]

Crop and plot.	Yield or ratio.								Average.	Probable error of mean ratio.
	Main field.		South field.				Main field.			
			II		IV					
	1915	1916	1915	1916	1915	1916	1915	1916		
Spring wheat:										
Plot B	32.1	18.5	30.4	17.8	31.3	17.0	21.8	18.7	23.5	
Plot E	31.7	18.8	24.8	15.5	25.6	16.0	27.1	18.2	22.2	
Ratio of E to mean	99	101	90	93	90	97	111	99	98	±1.6
Oats:										
Plot B	59.8	57.5	81.3	63.4	74.7	52.2	......	......	64.9	
Plot E	57.5	57.2	68.4	59.1	69.1	60.3	......	......	61.9	
Ratio of E to mean	98	100	91	96	96	107	......	......	98	±1.3
Barley:										
Plot B	57.0	26.7	58.3	28.5	52.7	24.0	......	......	41.2	
Plot E	49.7	29.2	50.8	26.5	54.3	27.3	......	......	39.6	
Ratio of E to mean	93	104	93	96	101	109	......	......	99	±2.0
Corn:										
Plot B	26.7	49.1	28.6	28.9	29.2	35.0	......	......	32.9	
Plot E	24.8	44.5	20.0	33.8	26.3	34.1	......	......	30.6	
Ratio of E to mean	96	95	82	108	95	99	......	......	96	±2.0
Flax:										
Plot B	13.1	5.2	......	......	......	......	......	......	9.2	
Plot E	14.8	6.9	......	......	......	......	......	......	10.9	
Ratio of E to mean	106	114	......	......	......	......	......	......	110	±3.4

The results are presented in detail in Table III. Of the 28 comparisons afforded, only 9 appear to be in favor of subsoiling. These are not confined to particular crops, to either year, or to either type of soil.

Production from all methods was heavy in both years. The mean ratio of all crops is 100, with a probable error of 1.6. With all crops except flax the average result is slightly against subsoiling, but by a margin less than the calculated probable error. Flax from an unduplicated pair of plots shows an apparent increase from subsoiling, but as this result with this crop in comparison with others is exactly contrary to those obtained at Huntley it must be concluded that the departures in each case are due to the experimental error. If this conclusion is correct, subsoiling has been without significant effect at this station.

BELLEFOURCHE FIELD STATION

The Bellefourche Field Station, near Newell, S. Dak., is located on a heavy clay soil derived from the decomposition of Pierre shale. From the soil at the surface there is a rapid change to broken but undecomposed shale. Near the bottom of the second foot there is a comparatively impervious layer of soil.

TABLE IV.—*Yields at the Bellefourche (S. Dak.) Field Station of spring wheat, winter wheat, oats, corn, and barley each year from 1909 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Crop and plot.	Yield or ratio.									
	1909	1910	1911	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:										
Plot B......	23.3	0.0	0.0	0.0	7.9	4.8	57.7	10.8	13.1	
Plot E......	28.5	0.0	0.0	0.0	6.8	4.7	55.6	16.6	14.0	
Ratio of E to mean..	110	......	......	......	93	99	98	121	104	± 3.8
Winter wheat:										
Plot B......	34.4	0.0	0.0	0.0	21.8	13.4	20.4	8.8	12.4	
Plot E......	29.3	0.0	0.0	0.0	18.7	14.7	25.2	8.5	12.1	
Ratio of E to mean..	92	......	......	......	92	105	111	98	100	± 2.9
Oats:										
Plot B......	46.9	0.0	0.0	6.6	15.8	24.7	119.7	23.1	29.6	
Plot E......	60.8	0.0	0.0	7.3	16.3	20.3	118.1	21.1	30.5	
Ratio of E to mean..	113	......	......	105	102	90	99	95	101	± 2.3
Barley:										
Plot B......	25.0	4.8	0.0	0.0	8.9	7.1	71.5	33.6	18.9	
Plot E......	33.8	0.0	0.0	0.0	7.8	6.3	78.9	29.2	19.5	
Ratio of E to mean..	115	0.0	......	......	93	94	105	93	83	±10.6
Corn:										
Plot B......	23.5	0.0	0.0	29.7	6.5	0.0	53.0	31.2	18.0	
Plot E......	20.8	0.0	0.0	26.3	9.4	0.0	47.7	32.3	17.1	
Ratio of E to mean..	94	......	......	94	118	......	95	102	101	± 3.2

Table IV presents eight years' results with spring wheat, winter wheat, oats, barley, and corn. During these years conditions have ranged from the drouth of 1911, which was so severe that all crops on all methods of preparation were total failures, to the favorable conditions of 1915, when the highest yields of spring grains yet recorded in experimental work in the Great Plains were obtained.

Of the 40 comparisons offered, only 11 are in favor of subsoiling. These are so evenly distributed throughout the different crops and years that no positive conclusion can be derived from them. A negative conclusion that subsoiling has afforded no protection against drouth is very clearly indicated. In the average of the eight years the differences in yield as a result of the two methods are measured in fractions of a bushel with every crop. The departures of the average ratios from 100 are all less than the probable error except in the case of barley, where the departure is less than twice the probable error. With this crop the difference in average number of bushels per acre is in one direction, while the departure of the average ratios is in the other. This is partly explained by the fact that in 1910 there was a production of nearly 5 bushels per acre on the fall plowing, while the subsoiled plot was a total failure. The mean ratio of all crops is 98, with a probable error of 2.5 This shows practically no effect in either direction as an average result of subsoiling.

ARDMORE FIELD STATION

The soil on the Ardmore (S. Dak.) Field Station is a heavy clay loam with a lighter subsoil. The subsoil is not uniform, but at depths of 3 feet or more it generally breaks into sand or gravel.

Three years' results, exclusive of the year 1914, when the crop was completely destroyed by hail, are available for study. One year the crops from many methods, including the two under study, were total failures. One year the yields were good, and one year the yields were very high.

Table V presents in detail the results with spring wheat, winter wheat, oats, barley, and corn at this station. With all crops except winter wheat, with which the better yield both years has been from subsoiling, the evidence is all against that practice. It failed with all crops to overcome the drouth of 1913, and actually appeared to reduce the yields of all crops but winter wheat both in the exceptionally productive year of 1915 and in the more normal year of 1916. The average ratio of all crops is 93, with a probable error of 3.1. There apparently is at this station a detrimental effect from subsoiling. The decrease in yield is not, however, enough greater than its probable error to make it all certain that it might not be effaced by continuation of the record.

TABLE V.—*Yields at the Ardmore (S. Dak.) Field Station of spring wheat, winter wheat, oats, barley, and corn each year from 1913 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Crop and plot.	Yield or ratio.					
	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:						
Plot B	0.0	(a)	49.5	17.5	22.3	
Plot E	0.0	(a)	43.3	12.8	18.7	
Ratio of E to mean			93	84	89	±3.8
Winter wheat:						
Plot B	0.0	(a)	29.2	29.8	19.7	
Plot E	0.0	(a)	33.3	34.5	22.6	
Ratio of E to mean			107	107	107	± .0
Oats:						
Plot B	0.0	(a)	75.4	42.2	39.2	
Plot E	0.0	(a)	59.4	25.0	28.1	
Ratio of E to mean			88	74	81	±5.9
Barley:						
Plot B	0.0	(a)	54.0	25.2	26.4	
Plot E	0.0	(a)	51.0	24.7	25.2	
Ratio of E to mean			97	99	98	±0.8
Corn:						
Plot B	0.0	0.0	43.7	28.7	18.1	
Plot E	0.0	0.0	32.9	26.6	14.9	
Ratio of E to mean			86	96	91	±4.2

[a] Crop destroyed by hail.

SCOTTSBLUFF FIELD STATION

The soil of the Scottsbluff (Nebr.) Field Station is a comparatively light sandy loam. At a depth varying from 5 to 8 feet there is a sharp break from this soil to either sand or Brule clay. Above this point the soil offers no unusual resistance either to the downward passage of water or to the development of roots.

Table VI presents five years' results with spring wheat, oats, barley, and corn at this station. Considered either by crops or by years, the only consistency to be noted is the heavier production on the subsoil plots in 1912. In the average of the five years the differences exhibited are very small and are less than the probable error with all crops except barley, where the difference only slightly exceeds the probable error.

TABLE VI.—*Yields at the Scottsbluff (Nebr.) Field Station of spring wheat, oats, barley, and corn each year from 1912 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield of B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Crop and plot.	Yield or ratio.						
	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:							
Plot B	6.3	7.8	6.7	16.2	5.7	8.5	
Plot E	12.3	6.3	9.5	6.8	7.0	8.4	
Ratio of E to mean	132	89	117	59	110	101	±9.3
Oats:							
Plot B	21.6	16.9	14.7	39.7	7.2	20.0	
Plot E	27.8	17.5	15.9	48.1	2.8	22.4	
Ratio of E to mean	113	102	104	110	56	97	±6.9
Barley:							
Plot B	23.5	......	4.4	35.4	10.0	18.3	
Plot E	24.8	......	5.2	26.0	6.0	15.5	
Ratio of E to mean	103	......	108	85	75	93	±6.2
Corn:							
Plot B	38.0	32.2	20.1	10.1	22.1	24.5	
Plot E	40.0	26.1	14.2	13.6	23.2	23.4	
Ratio of E to mean	103	90	83	115	102	99	±4.1

ARCHER FIELD STATION

The soil of the field station at Archer, Wyo., is a medium-dark sandy loam with a little fine gravel distributed very evenly through it. Below the second foot the proportion of sand increases, and at a depth varying from 3 to 6 feet pure gravel is reached.

Table VII presents three years' results with spring wheat, winter wheat, and oats, and two years' results with corn and barley at this station. Of the 13 comparisons afforded only 5 appear to be in favor of subsoiling. Only with corn has the heavier yield for more than one year been from the subsoiled plot. The average differences exhibited by all crops are insignificant when considered in connection with the probable error.

TABLE VII.—*Yields at the Archer (Wyo.) Field Station of spring wheat, winter wheat, oats, barley, and corn each year from 1914 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yield of corn in pounds of stover; other crops in bushels of grain per acre]

Crop and plot.	Yield or ratio.				
	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:					
Plot B	7.5	23.7	2.4	11.2	
Plot E	5.8	25.0	1.0	10.6	
Ratio of E to mean	87	103	59	83	± 9.6
Winter wheat:					
Plot B	0.0	24.7	7.4	10.7	
Plot E	0.0	24.2	2.4	8.9	
Ratio of E to mean	....	99	49	74	±21.1
Oats:					
Plot B	14.5	35.9	3.7	18.0	
Plot E	9.4	34.7	5.6	16.6	
Ratio of E to mean	79	98	120	99	± 8.4
Barley:					
Plot B	....	29.8	5.2	17.5	
Plot E	....	35.8	4.2	20.0	
Ratio of E to mean	....	109	89	99	± 8.5
Corn:					
Plot B	1,090	3,900	(a)	2,495	
Plot E	1,130	4,450	(a)	2,790	
Ratio of E to mean	102	107	....	105	± 2.1

a Weights lost.

AKRON FIELD STATION

The soil of the field station at Akron, Colo., is a clay loam locally known as "hard land." It is characterized in the native vegetation by a growth of short grass.

Table VIII presents an unbroken record of eight years' results with spring wheat, oats, barley, and corn, and seven years' results with winter wheat at this station. The E plots were subsoiled in the fall of 1908, 1909, 1812, 1913, and 1914. Of the 39 comparisons presented in this table only 7 show the higher yields from the subsoiled plot. The only consistency in the distribution of these among the different crops or years is that in 1909 all four crops under trial that year showed the heavier yield on the subsoiled plot. In the average of the eight years the better yield of each crop has been obtained from the plot not subsoiled. The average decrease in yield as a result of subsoiling ranges from 1.7 bushels per acre with winter wheat to 3.4 bushels per acre with corn. The

average ratio for all crops is 85. This station shows the clearest cut and most decisive results of any station where subsoiling has been investigated.

TABLE VIII.—*Yields at the Akron (Colo.) Field Station of spring wheat, winter wheat, oats, barley, and corn each year from 1909 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Crop and plot.	Yield or ratio.									
	1909	1910	1911	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:										
Plot B	10.3	6.2	4.1	20.7	0.8	12.2	25.8	3.8	10.5	
Plot E	11.2	5.5	1.5	16.0	.5	9.8	23.7	1.7	8.7	
Ratio of E to mean	104	94	54	87	77	89	96	62	83	±4.4
Winter wheat:										
Plot B	......	10.3	6.8	26.7	2.0	24.8	20.8	4.2	13.7	
Plot E	......	6.9	3.3	21.2	3.2	24.5	21.0	3.8	12.0	
Ratio of E to mean	......	80	65	89	123	99	100	95	93	±4.4
Oats:										
Plot B	14.1	8.0	15.9	46.9	.6	36.9	57.2	7.2	23.4	
Plot E	16.1	11.3	8.4	35.3	0.0	30.3	57.5	4.1	20.4	
Ratio of E to mean	107	117	69	86	0.0	90	100	73	80	±7.9
Barley:										
Plot B	16.8	10.5	16.3	27.9	3.1	36.7	47.9	5.0	20.5	
Plot E	19.8	6.9	5.2	22.5	1.5	27.9	52.3	4.2	17.5	
Ratio of E to mean	108	79	48	89	65	86	104	91	84	±4.7
Corn:										
Plot B	27.3	18.3	0.0	46.9	9.9	17.3	29.2	4.8	19.2	
Plot E	32.8	12.7	0.0	37.1	4.3	13.9	22.3	3.2	15.8	
Ratio of E to mean	109	82	......	88	61	89	87	80	85	±3.2

HAYS FIELD STATION

The soil of the field station on which the experimental work has been conducted at Hays, Kans., is a heavy silt loam. Penetration of water to the lower depths is slow, the very compact soil in the third foot offering marked resistance to its downward passage.

Table IX presents from this station a record beginning with 1907 for winter wheat and corn; 1908 for spring wheat, oats, and barley; 1911 for kafir; and 1912 for milo. In the average of all the years the higher yields are from the subsoiled plots with all crops except barley, which shows no difference. With corn the higher yield has been obtained

every year from the subsoiled plot. Winter wheat, corn, and kafir show increases amounting to more than three times the probable error. With the other crops the differences are less than the probable error. This is the only station at which the averages of all crops show a ratio of 100 or more on the subsoiled plot. With some of the crops the average yields have been so small as to be unprofitable from either method. It should be noted that this station has the highest annual precipitation of any station under study. As noted later in discussing the use of dynamite and deep plowing, the results of those practices do not support those obtained from subsoiling.

TABLE IX.—*Yields at the Hays (Kans.) Field Station of spring wheat, winter wheat, oats, barley, corn, kafir, and milo each year from 1907 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of all crops in bushels per acre]

Crop and plot.	Yield or ratio.											
	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:												
Plot B	......	4.5	(a)	9.6	0.0	15.2	0.5	(b)	7.0	0.7	5.4	
Plot E	......	5.2	(a)	12.6	0.0	12.7	1.3	(b)	8.3	.3	5.8	
Ratio of E to mean	......	107	......	114	......	91	144	......	108	60	104	±7.2
Winter wheat:												
Plot B	18.2	23.2	(a)	27.8	.3	13.8	2.3	24.8	13.1	22.7	16.2	
Plot E	13.6	30.5	(a)	39.8	.3	20.1	4.1	25.3	14.9	27.6	19.6	
Ratio of E to mean	86	114	......	118	100	119	128	101	106	110	109	±2.9
Oats:												
Plot B	......	3.7	(a)	16.6	0.0	37.7	10.6	27.0	25.1	6.0	15.8	
Plot E	......	17.9	(a)	24.5	0.0	45.1	21.8	26.6	29.2	1.0	20.8	
Ratio of E to mean	......	166	......	119	......	109	135	99	108	29	109	±9.1
Barley:												
Plot B	......	12.4	(a)	19.7	0.0	28.8	4.0	16.7	26.8	10.1	14.8	
Plot E	......	14.8	(a)	19.3	0.0	33.8	4.6	15.2	22.4	8.2	14.8	
Ratio of E to mean	......	109	......	99	......	108	107	95	91	90	100	±2.4
Corn:												
Plot B	12.2	3.1	7.9	6.8	(c)	1.8	(c)	5.5	14.9	3.6	7.0	
Plot E	13.6	8.8	8.0	7.4	(c)	5.5	(c)	6.4	16.5	4.3	8.8	
Ratio of E to mean	105	148	101	104	......	151	......	108	105	109	116	±5.2
Kafir:												
Plot B	......	......	......	......	.6	12.8	(c)	16.3	67.4	.4	19.5	
Plot E	......	......	......	......	1.0	26.1	(c)	23.0	66.6	.7	23.5	
Ratio of E to mean	......	......	......	......	125	134	......	117	99	127	120	±4.2
Milo:												
Plot B	......	......	......	......	(c)	16.2	(c)	15.2	53.5	1.4	21.6	
Plot E	......	......	......	......	(c)	17.5	(c)	17.6	48.8	1.3	21.3	
Ratio of E to mean	......	......	......	......	......	104	......	107	95	96	101	±2.4

[a] Destroyed by hail. [b] Destroyed by soil blowing. [c] Destroyed by insects.

GARDEN CITY FIELD STATION

The work at the field station at Garden City, Kans., is on a high upland. The soil is a light silt loam. With the exception of the accumulated humus near the surface it is practically uniform to a depth of at

least 15 feet. The development of roots is limited only by the depth to which water is available and the physiological character of the plant.

Table X presents the results of seven years' work at this station, exclusive of 1913, when the crops were destroyed by hail. In 1911, which is included in the averages, all small-grain crops failed from drought so extreme that it was not overcome by any method under trial. In 1914 the higher yield of all five crops under trial was on the subsoiled plot. This was the only year, however, when there was a consistent, marked difference in the results from the two methods. With none of the five crops has the average departure in either direction from the mean been greater than 4 per cent. Only in the case of wheat, which has a mean ratio of 103, with a probable error of 2.5, is the departure from the mean greater than the probable error. The results are conclusive in showing that subsoiling is without significant effect at this station.

TABLE X.—*Yields at the Garden City (Kans.) Field Station of spring wheat, winter wheat, oats, barley, and corn each year from 1909 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yield of corn in total pounds; other crops in bushels per acre]

Crop and plot.	Yield or ratio.									
	1909	1910	1911	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:										
Plot B.....	3.2	5.2	0.0	6.3	(a)	4.3	12.6	0.0	4.5	
Plot E.....	2.9	5.2	0.0	7.7	(a)	5.3	12.0	0.0	4.7	
Ratio of E to mean..	95	100	......	110	......	110	98	......	103	±2.5
Winter wheat:										
Plot B.....	0.0	0.0	0.0	0.0	(a)	6.3	10.0	0.0	2.3	
Plot E.....	0.0	0.0	0.0	0.0	(a)	6.7	9.9	0.0	2.4	
Ratio of E to mean..	......	......	......	......	......	103	99	......	101	±1.7
Oats:										
Plot B.....	3.2	10.3	0.0	23.1	(a)	8.1	32.7	3.0	11.5	
Plot E.....	2.6	10.0	0.0	15.9	(a)	17.3	30.9	3.0	11.4	
Ratio of E to mean..	90	99	......	82	......	136	97	100	101	±4.5
Barley:										
Plot B.....	4.8	5.4	0.0	9.0	(a)	15.2	24.2	3.0	8.8	
Plot E.....	3.7	5.2	0.0	8.5	(a)	17.3	21.5	4.0	8.6	
Ratio of E to mean..	87	98	......	97	......	106	94	114	99	±2.6
Corn:										
Plot B.....	(b)	(b)	1,400	4,620	(a)	3,040	1,900	1,200	2,440	
Plot E.....	(b)	(b)	750	4,500	(a)	4,840	1,800	2,260	2,830	
Ratio of E to mean..	......	......	70	99	......	123	97	131	104	±7.8

[a] Crop destroyed by hail. [b] Weights lost.

AMARILLO FIELD STATION

The soil at the field station at Amarillo, Tex., is a heavy clay silt. The storage of water and the development of the feeding roots of the crop are apparently interfered with by comparatively impervious soil in the third foot.

Eight years' results with spring wheat, winter wheat, oats, and barley, and nine years' with corn are presented in Table XI. The year 1910 is not included, as the location of the station was changed, and the preparation of the land was uniform for that year. Of the 41 comparisons afforded in this table less than one-third show the higher yield to have been from the subsoiled plot. There is no consistency in the distribution of these either by years or by crops. In the average of the entire period the results with all crops are against subsoiling. The average decrease in yields as a result of subsoiling ranges from 1 bushel per acre with spring wheat to 3.2 bushels with oats. With all crops except corn the decrease due to subsoiling is more than twice the probable error.

TABLE XI.—*Yields at the Amarillo (Tex.) Field Station of spring wheat, winter wheat, oats, barley, and corn each year from 1907 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yield of all crops in bushels per acre]

Crop and plot.	Yield or ratio.										
	1907	1908	1909[a]	1911	1912	1913	1914	1915	1916	Average.	Probable error of mean ratio.
Spring wheat:											
Plot B	......	14.0	2.8	10.0	8.5	1.8	12.8	11.0	7.0	8.5	
Plot E	......	16.2	4.0	11.3	4.2	.8	12.3	10.3	1.2	7.5	
Ratio of E to mean	......	107	118	106	66	62	98	97	29	85	±7.9
Winter wheat:											
Plot B	......	14.3	0.0	3.5	7.2	1.3	23.0	24.4	3.6	9.7	
Plot E	......	16.5	0.0	1.2	3.3	1.3	19.3	19.7	4.5	8.2	
Ratio of E to mean	......	107	......	51	63	100	91	89	111	87	±6.1
Oats:											
Plot B	......	32.2	0.0	27.5	14.1	2.5	30.9	31.7	12.2	18.9	
Plot E	......	28.1	0.0	19.2	8.8	4.1	30.6	34.2	.9	15.7	
Ratio of E to mean	......	93	......	82	77	124	100	104	14	85	±8.0
Barley:											
Plot B	......	13.2	5.8	11.7	1.7	0.0	16.7	17.3	3.8	8.8	
Plot E	......	11.9	0.0	10.3	1.5	0.0	17.1	16.0	.2	7.1	
Ratio of E to mean	......	95	0.0	94	94	......	101	96	10	70	±12.0
Corn:											
Plot B	1.4	22.9	2.7	9.2	.7	0.0	3.6	54.0	7.2	11.3	
Plot E	1.1	25.7	1.7	7.1	1.0	0.0	5.1	46.4	3.7	10.2	
Ratio of E to mean	88	106	77	87	118	......	117	92	68	94	±4.7

[a] No record for 1910 on account of change in location of station.

TUCUMCARI FIELD STATION

The soil of the field station at Tucumcari, N. Mex., is of a residual type and is classified by the Bureau of Soils as a fine sand. The sand extends down to a depth of from 1 to 3 feet, gradually blending into a clay which continues in many places to a depth of at least 135 feet.

Table XII presents three years' results with kafir, milo, sorghum, broom corn, and cotton at this station. Of the 15 comparisons afforded in this table only 2 are in favor of subsoiling. These are kafir in 1914 and broom corn in 1915. This evidence seems conclusive that subsoiling here is at least an unnecessary if not a detrimental practice.

TABLE XII.—*Yields at the Tucumcari (N. Mex.) Field Station of kafir, milo, sorghum, broom corn, and cotton each year from 1914 to 1916, inclusive, on plot E, subsoiled, and plot B, not subsoiled but otherwise similarly treated, together with the average of each method for the entire period of years; the ratio of the yield on E to the mean of the yield on B and E each year; the mean ratio; and the probable error of the mean ratio*

[Yields of kafir and milo in bushels; sorghum in pounds of forage; broom corn in pounds of brush; and cotton in pounds of seed cotton per acre]

Crop and plot.	Yield or ratio.				
	1914	1915	1916	Average.	Probable error of mean ratio.
Kafir:					
Plot B	34.9	39.8	18.0	30.9	
Plot E	38.5	39.8	18.0	32.1	
Ratio of E to mean	105	100	100	102	±1.4
Milo:					
Plot B	45.8	46.8	9.0	33.9	
Plot E	36.2	41.1	7.2	28.2	
Ratio of E to mean	88	94	89	90	±1.4
Sorghum:					
Plot B	5,320	5,020	5,560	5,300	
Plot E	5,080	4,980	4,600	4,887	
Ratio of E to mean	98	100	91	96	±2.2
Broom corn:					
Plot B	583	500	420	501	
Plot E	490	780	190	487	
Ratio of E to mean	91	122	62	92	±12.2
Cotton:					
Plot B	838	520	380	579	
Plot E	773	340	205	439	
Ratio of E to mean	96	79	70	82	±5.8

COMPARATIVE RESULTS WITH SUBSOILING DIFFERENT CROPS

The comparative results with different crops as shown in Table XIII and figures 2 and 3 scarcely warrant any conclusion that one crop is affected differently than another by subsoiling. The average ratios with

spring wheat, winter wheat, oats, and barley, which range from 94 to 97, with probable errors ranging from 2 to 2.6, certainly do not indicate any difference in the relative effect of subsoiling upon these crops. Corn

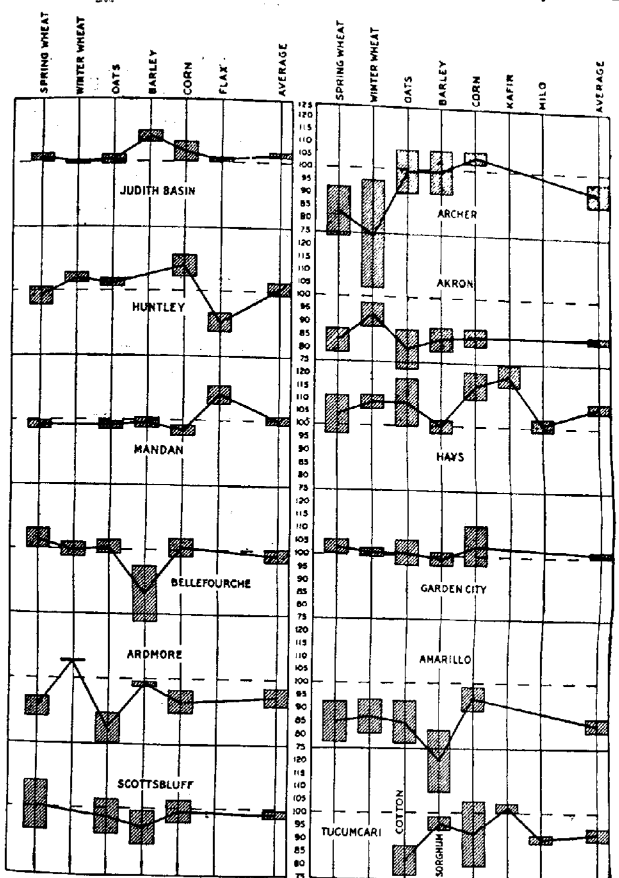

FIG. 2.—Ratio of the yield for each crop at each station of plot E (subsoiled) to the mean of the yield of plot B (not subsoiled) and plot E (subsoiled) and the averageof all crops at each station. The shaded areas are delimited by the probable error of each ratio. They mark the zones within which the chances are even that the results of a repetition of the experiments would fall.

at the same stations has a ratio of 100, with a probable error of 1.8. While the difference between this and the other crops is not great enough to make it in any way conclusive, it might perhaps indicate a slightly better response from this crop.

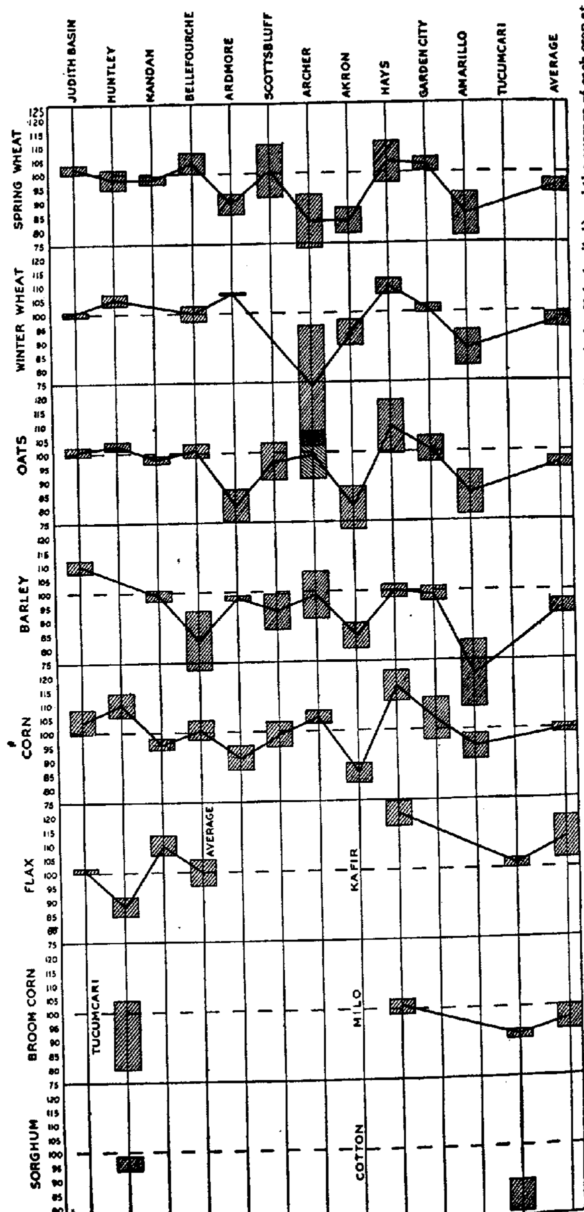

FIG. 3.—Ratio of the yield for each crop at each station of plot E (subsoiled) to the mean of the yield of plot B (not subsoiled) and plot E (subsoiled) and the average of each crop at all stations. The shaded areas are delimited by the probable errors. They mark the zones within which the chances are even that the results of a repetition of the experiments would fall.

When studied by the number of trials that resulted either in favor of or against subsoiling, it was found that, while with oats, corn, and winter wheat slightly more than half the trials resulted in favor of subsoiling and with spring wheat and barley slightly less than half, the deviations were not enough greater than their probable errors to make them significant.

The effect upon flax is apparently not different from that on the small-grain crops.

TABLE XIII.—*Summary table showing mean ratio*[a] *and probable error of mean of each crop at each station as shown in Tables I to XII, inclusive, and the general mean for each crop at all stations, and of all crops at each station*

Crop and factor.	Judith basin.	Huntley.	Mandan.	Belle-fourche.	Ardmore.	Scotts-bluff.	Archer.	Akron.	Hays.	Garden City.	Amarillo.	Tucum-cari.	Mean and probable error.
Spring wheat:													
Ratio..........	102	98	98	104	89	101	83	83	104	105	85	......	95±2.1
Probable error±	1.3	3.4	1.6	3.8	3.8	9.3	9.6	4.4	7.2	2.5	7.9	......	
Winter wheat:													
Ratio..........	100	105	......	100	107	......	74	93	109	101	87	......	97±2.6
Probable error±	.9	2.0	......	2.9	0.0	......	21.4	4.4	2.9	1.7	6.1	......	
Oats:													
Ratio..........	101	103	98	101	81	97	99	80	109	101	85	......	96±2.0
Probable error±	1.9	1.5	1.3	2.3	5.9	6.9	8.4	7.9	9.1	4.5	8.0	......	
Barley:													
Ratio..........	110	......	99	83	98	93	99	84	100	99	70	......	94±2.5
Probable error±	2.2	......	2.0	10.6	0.8	6.2	8.5	4.7	2.4	2.6	12.0	......	
Corn:													
Ratio..........	104	110	96	101	91	99	105	85	116	104	94	......	100±1.8
Probable error±	4.2	4.1	2.0	3.2	4.2	4.1	2.1	3.2	5.2	7.8	4.7	......	
Flax:													
Ratio..........	101	88	110	......	......	......	......	......	......	......	......	......	100±4.6
Probable error±	.9	3.7	3.4	......	......	......	......	......	......	......	......	......	
Kafir:													
Ratio..........	......	......	......	......	......	......	......	......	120	......	......	102	111±7.6
Probable error±	......	......	......	......	......	......	......	......	4.2	......	......	1.4	
Milo:													
Ratio..........	......	......	......	......	......	......	......	......	101	......	......	90	96±4.6
Probable error±	......	......	......	......	......	......	......	......	2.4	......	......	1.4	
Broom corn:													
Ratio..........	......	......	......	......	......	......	......	......	......	......	......	92	
Probable error±	......	......	......	......	......	......	......	......	......	......	......	12.2	
Sorghum:													
Ratio..........	......	......	......	......	......	......	......	......	......	......	......	96	
Probable error±	......	......	......	......	......	......	......	......	......	......	......	2.2	
Cotton:													
Ratio..........	......	......	......	......	......	......	......	......	......	......	......	82	
Probable error±	......	......	......	......	......	......	......	......	......	......	......	5.8	
Mean ratio.......	103	101	100	98	93	98	92	85	108	102	84	92	
Probable error..±	1.0	2.6	1.6	2.5	3.1	1.2	4.6	1.4	2.0	.7	2.5	2.2	

[a] Ratio based on yields of crops at the different stations as follows: Seed cotton, broom-corn brush, and sorghum forage at Tucumcari; corn stover at Judith Basin, Archer, and Garden City; ear corn at Huntley, Mandan, Bellefourche, Ardmore, Scottsbluff, Akron, Hays, and Amarillo; all other crops on yields of grain at all stations.

Kafir at the two stations from which results with this crop have been obtained appears to have given a markedly favorable response to subsoiling in comparison with the effect of that practice upon other crops, particularly milo. This subject is being given much fuller investigation at a number of additional stations to which the crop is adapted.

The results with sorghum, cotton, and broom corn being from a single station can scarcely be compared with those obtained with other crops.

The grand average ratio of all crops at all stations is 97, with a probable error of 0.9. This average, of course, is meaningless in its possible application to any crop or any station. It would be influenced by the distribution of the observations among conditions that were either favorable or unfavorable in their response. The only purpose of introducing it here is to show the relative lack of any effect, and particularly of any favorable effect, of the practice of subsoiling as applying to a wide territory and a wide range of crops.

This lack of effect of the practice when applied generally to all crops and to the entire area is further confirmed when the results are studied in another way. Exclusive of years of total failure there are 353 trials here reported. In 15 of these there was no difference in the yield from the two methods, in 153 cases the higher yield was obtained from the subsoiled plot, and in 185 cases from the plot not subsoiled.

COMPARATIVE RESULTS WITH SUBSOILING IN FAVORABLE AND UNFAVORABLE YEARS

The relative effect of subsoiling in favorable and unfavorable years is a question that naturally arises. There have been a number of cases in which the crops by both methods have been a total failure. *There have been some cases in which the plot not subsoiled produced a small crop when the subsoiled plot was a total failure. There has been no case in the history of the experiments when the reverse was true.* In order to obtain definite information on the subject the results were divided into two groups; one group containing the ratios from each station for those years when the yield was above the average for that station and the other group containing the ratios of those years when the yield was below the average. Those groups showed average ratios of 100 for the years of better production and 94.4 for the years of poorer production.

In the years above the average in production 75 trials resulted in favor of subsoiling, 81 trials in favor of ordinary plowing, and in 8 trials the same yield was obtained from each method. In the years below the average in production 78 trials resulted in favor of subsoiling, 104 in favor of ordinary plowing, and 7 showed no difference in the yields from the two methods.

These results indicate that, on the average, subsoiling, instead of overcoming the effects of drouth, actually intensifies them. In this connection it should be recognized that, while low yields are in some cases caused by fungus diseases, by insect attacks, or by unfavorable temperature or other weather conditions, the one primary predominating cause of low yields has been the lack of sufficient soil moisture at some time during the growth of the crop.

DEEP TILLING BY THE USE OF DYNAMITE OR SPECIAL PLOWS

Experiments have been conducted with both dynamite[1] and the Spalding deep-tilling machine at the Hays and Akron stations, and with dynamite at the Ardmore, Bellefourche, and Judith Basin stations.

HAYS FIELD STATION

DEEP TILLING BY THE USE OF DYNAMITE AND SPECIAL PLOWS

In 1913 a series of experiments was started at Hays, Kans., to determine the effect of different methods of preparing the land for winter wheat in a series of three-year rotations of fallow, winter wheat, and kafir. In this series four rotations, No. 501, 502, 503, and 504, are identical except as noted below. In No. 501 the plowing for the fallow is done with a Spalding deep-tilling machine, which plows the soil to a depth of from 12 to 14 inches. This plowing is done in the fall, preceding the fallow season, or practically an entire year before seeding to winter wheat. In rotation 502, dynamite is used in the fall. After dynamiting, the land is furrowed with a lister, the same as in rotations 503 and 504. In dynamiting, 18 shots of half sticks of 20 per cent powder placed 3 feet deep are fired on the tenth-acre plot, the distance between the shots being 16 feet. The plots to be fallowed in rotations 503 and 504 are furrowed out with the lister in the fall preceding the fallow season. These two rotations are identical except that the wheat stubble in No. 503 is disked after harvest, while that in No. 504 receives no cultivation until both are furrowed with a lister in the fall. All the fallow plots are given necessary cultivation to keep them free from vegetation during the fallow year. These rotations were begun in the spring of 1913, but the crops that year were a failure. The first dynamiting and deep tilling was done in the fall or 1913. The land so treated was fallow in 1914, so the first crop of wheat on plots differing in their treatment was harvested in 1915. The first kafir following the wheat on the plots differently treated was produced in 1916.

In Table XIV are given the yields of both winter wheat and kafir for the three years 1914, 1915, and 1916. There are thus shown one wheat crop, 1914, on land uniform in preparation, and two wheat crops, 1915 and 1916, on land differing in its treatment. With the kafir crop the preparation of the various rotations was uniform for the crops of 1914 and 1915, but was differentiated for the crop of 1916. To facilitate comparisons, the data in this table are shown in two forms. First, the yield in bushels, and second, the ratio of these yields to the mean yield of the four plots for each year. The data from plots differing in their treatment are shown in boldfaced type.

[1] The E. I. du Pont de Nemours Powder Co. furnished the material for the dynamiting experiments and experts to direct the operations at the different field stations.

It appears from these results that no significant differences in the yields have resulted from the differences in preparation. There are no greater differences exhibited between the deep-tilled or dynamited plots and those not so treated than are shown between the same plots when the preparation of the land was uniform, or are shown between rotations 503 and 504, which are practically the same in their treatment.

TABLE XIV.—*Yields at the Hays (Kans.) Field Station for the years 1914 to 1916, inclusive, from four 3-year rotations of fallow, winter wheat, and kafir, showing the results of dynamiting and deep tillage of fallow*

Rotation and crop.	Yield in bushels.			Ratio of yield to mean.		
	1914	1915	1916	1914	1915	1916
Rotation 501:						
Fallow, deep-tilled	......	......	......	......	......	......
Winter wheat	24.8	14.9	38.8	98	108	107
Kafir	2.6	51.2	12.7	52	104	105
Rotation 502:						
Fallow, dynamited	......	......	......	......	......	......
Winter wheat	24.3	13.5	32.9	96	98	91
Kafir	5.0	46.4	9.5	100	94	79
Rotation 503:						
Fallow, listed	......	......	......	......	......	......
Winter wheat	25.5	14.4	35.5	100	104	98
Kafir	6.4	46.8	11.4	128	93	94
Rotation 504:						
Fallow, listed	......	......	......	......	......	......
Winter wheat	26.9	12.5	37.8	106	91	104
Kafir	5.9	52.2	14.7	118	106	121

AKRON FIELD STATION

DEEP TILLAGE BY THE USE OF DYNAMITE

At the field station at Akron, Colo., a square of prairie sod was divided checkerboard fashion into 16 plots each 4 rods square, separated by the necessary alleys, making 0.1 acre in each plot. The designation of the plots by letters is similar to that at Ardmore (fig. 4). On August 26 and 27, 1912, the two center tiers of plots running north and south were dynamited. The soil was quite dry at this time. Twenty per cent dynamite was used, the shots being placed 15 feet apart, 16 holes to the plot. The shots were fired at a depth of 30 inches, ½ pound of dynamite being used for each charge. After a rain which put the soil in good condition the entire block of plots was broken, September 16 to 18, and the sod rolled flat with a roller.

In the spring of 1913 the eight plots on the north, four of which had been dynamited and four of which had not, were given the necessary disking and harrowing to make as good a seed bed as possible, and were

then seeded to durum wheat. The eight plots composing the two tiers on the south side of the block were replowed and the seed bed prepared with the disk and harrow. These eight plots were planted to corn.

The season proved very dry, and both crops were a failure on all plots. The late breaking was not considered a favorable preparation because of the lack of water in storage in the soil. Under favorable conditions of spring and summer rainfall it would have produced a crop, but under the conditions that actually obtained only failure was to be expected.

No effect of the blasting could be observed in the crop. Where a charge of dynamite had been set, there was a slight depression and the wheat in this space was an inch or two taller than that surrounding it, but no taller than it was in other depressions not caused by blasting.

The wheat plots were plowed 5 inches deep on September 23. The corn plots were plowed 5 inches deep on July 15, when the corn was so badly damaged by drought that it was evident there would be no crop produced. The same plots were replanted to wheat and corn in 1914. The yields are given in Table XV. The difference between the average yield of wheat on the four plots dynamited and on the four plots not dynamited is well within the probable error of the series. The average yield of corn on the plots not dynamited was 14.1 bushels, with a probable error of 1.5 bushels, while on the dynamited plots the average yield was 18.6 bushels, with a probable error of 1.3 bushels. Even the apparent increase in yield, which the probable error shows is open to question that it may have been due to accidental causes, is in no way commensurate with the expense of dynamiting, even if the effect persisted for a number of years.

TABLE XV.—*Yields of wheat and corn (bushels per acre) in 1914 at the Akron (Colo.) Field Station on land dynamited in 1912, and on control plots not dynamited*

Crop and treatment.	Plot and yield.				Average.	Probable error.
Wheat:						
Not dynamited	A 17.8	C 15.7	K 13.0	M 15.3	15.5	±0.6
Dynamited	B 14.4	D 16.1	J 14.0	L 15.6	15.0	±0.4
Corn:						
Not dynamited	E 17.6	G 10.4	O 11.6	Q 16.7	14.1	±1.5
Dynamited	F 13.4	H 20.0	N 18.9	P 22.2	18.6	±1.3

In 1915 the eight plots constituting the west half of the block were planted to corn and the eight plots constituting the east half to wheat. The average yield of ear corn was 33.2 bushels per acre. The average yield of the four plots dynamited in the fall of 1912 was exactly the same

as that of the four not dynamited. The individual yields of the four wheat plots following wheat were lost by mixture. There was no difference in height, stand, or estimated yield. Of the four wheat plots following corn two were dynamited in 1912. Their yield was 18.2 bushels on plot J and 19.2 bushels on plot L. Plot K, not dynamited, yielded 16.2 bushels, and plot M, not dynamited, 18.2 bushels. This shows an average gain of 1.5 bushels per acre in favor of the pair of dynamited plots, but exactly the same difference is shown between the pairs J-K and L-M that do not differ in their treatment.

The experiment was continued in 1916 by seeding the north half to corn and the south half to wheat as in 1914. The season proved unfavorable, and these plots were badly damaged by rabbits. As no differences were apparent that could be attributed to the use of the dynamite, the yields were not determined.

DEEP TILLAGE BY THE USE OF SPECIAL PLOWS

The land used in the deep-tillage experiment is a block 37 rods long north and south and 10 rods wide, divided into 16 plots 10 rods long and 2 rods wide containing ⅛ acre each. Bare, cultivated alleys 4 feet 7 inches wide separate the plots. The land was broken from prairie sod during the summer of 1907, but a record of its treatment for the seasons of 1908 and 1909 is not available. During the season of 1910 the west half of all the plots produced a light crop of oats, and the east half was planted to cultivated crops of corn, sorghum (*Andropogon sorghum*), and sunflowers (*Helianthus annuus*). The soil is a sandy loam, increasing in heaviness toward the north. The north half of the block slopes slightly to the north. The 16 plots are designated by the letters A to Q, reading from the south.

In the spring of 1911 an experiment was outlined to test the effect of deep tillage, as compared with ordinary plowing, for spring wheat and corn in different combinations of wheat and corn and the two tillage depths. Eight of the sixteen plots were to be deep-tilled and eight plowed in the ordinary manner each year; eight plots to be cropped to wheat and eight to corn in such manner as to afford different combinations of these crops and tillage methods.

The Spalding deep-tilling machine used in this experiment was received too late to prepare for wheat in 1911. The eight plots to be planted to corn were plowed on May 17, four of them deep and four shallow, as called for in the outline. The corn crop for this year follows the outline as regards depth of tillage, but was on land which was uniform with reference to crop sequence. The eight plots that should have been in wheat were fallow during the summer. They were plowed on July 13, four of them with the ordinary plow and four with the deep-tillage machine. Winter wheat was sown in the fall on four of the fallow plots and four of the plots that had been in corn. The preparation for the

crop of 1913 follows the outline in its entirety as regards depth of tillage. In the particular of crop sequence the four corn plots and the four wheat plots that should have followed wheat were on fallow land. Winter wheat was used in this experiment only the one year, durum wheat having been grown since the first crop.

Ordinary plowing has been done uniformly to the depth of 7 inches with a moldboard plow of the sulky type. Deep tilling has been done to the depth of 14 inches each year. Plowing for wheat has been done in the fall; plowing for corn has been done in the spring of each year, except in preparation for the crop of 1913.

The outline was departed from in preparing for the crop of 1916. The 4 corn plots that were to be sown to wheat were not plowed, but were double-disked in preparation for seeding. The 12 other plots—4 corn plots to be planted to corn, 4 wheat-stubble plots to be planted to corn, and 4 wheat-stubble plots to be planted to wheat—were all plowed 6 inches deep in the spring of 1916.

The results of this experiment for the six years 1911 to 1916, inclusive, are given in Table XVI. The yields given in this table are arranged under 16 heads: (1) Wheat following wheat on land deep-tilled each year, plot L; (2) wheat following wheat the first year after deep tillage on land deep-tilled every other year, plot J in the odd years and M in the even; (3) wheat following wheat the second year after deep tillage on land deep-tilled every other year, plot M in the odd years and J in the even; (4) wheat following wheat on land ordinary plowed each year, plot K; (5) wheat following corn on land deep-tilled each year, plot D in the odd years and N in the even; (6) wheat following corn the first year after deep tillage on land deep-tilled every other year, plot B in the odd years and O in the even; (7) wheat following corn the second year after deep tillage on land deep-tilled every other year, plot C in the odd years and P in the even; (8) wheat following corn on land ordinary plowed each year, plot A in the odd years and Q in the even. (9–16) Eight similar combinations of crop sequence and tillage method occur with the corn crop.

At the right of Table XVI are two averages. The first needs no explanation, being the average of each method for the entire period of years. Under the corn crop the grain average is the average of the three years when grain was produced and the fodder average is the average of the total weights for the three years when little or no grain was produced. The second average is the average of the two crop sequences on similar conditions of depth of cultivation.

The results given in Table XVI show a rather striking effect of crop sequence. Wheat following corn and corn following corn are both markedly better than the same crops following wheat. This positive result is the more striking when considered in connection with the lack of difference in the average yields resulting from the very marked dif-

ferences in the depth of plowing. Where wheat follows wheat the three combinations, (1) deep-tilled each year, (2) the first crop after deep tillage, and (3) the second crop after deep tillage on plots alternately deep- and shallow-tilled, exhibit no difference. The plot that received no deep tillage shows an apparent increase over any of these combinations, but a careful analysis of the results of the four plots from year to year points very strongly to the belief that this apparent increase may be within the limits of the experimental error.

TABLE XVI.—*Yields at Akron (Colo.) Field Station of wheat and corn in deep-tillage experiment for the years 1911 to 1916, inclusive*

Crop and treatment.	Previous crop.	Plot.[a]	Yield (bushels per acre).[b]									
			1911	1912	1913	1914	1915	1916	Averages.			
									Grain.	Fodder.	Similar treatment after both wheat and corn.[c] Grain.	Similar treatment after both wheat and corn.[c] Fodder.
WHEAT.												
Deep tillage each year.	Wheat.	L	......	22.5	0.3	17.1	25.5	3.5	13.8	......	16.2	......
First crop after deep tillage.	...do....	J-M	......	22.9	.3	16.4	24.5	3.2	13.5	......	18.0	......
Second crop after deep tillage.	...do....	M-J	......	29.2	.2	14.8	22.7	2.1	13.8	......	18.7	......
Ordinary plowing...	...do....	K	......	32.8	.3	17.7	22.4	2.7	15.2	......	21.0	......
Deep tillage each year.	Corn...	D-N	......	33.0	3.5	18.7	29.6	8.1	18.6	......	......	......
First crop after deep tillage.	...do....	B-O	......	40.0	9.6	21.9	33.3	7.7	22.5	......	......	......
Second crop after deep tillage.	...do....	C-P	......	45.9	5.3	28.1	30.9	7.6	23.6	......	......	......
Ordinary plowing...	...do....	A-Q	......	54 7	10.5	31.9	30.0	6.4	26.7	......	......	......
CORN.[b]												
Deep tillage each year.	Corn...	F	1,000	45.2	2,320	20.1	35.6	1,360	33.6	1,560	29.3	1,606
First crop after deep tillage.	...do....	H-E	864	40.7	2,320	16.9	27.0	1,600	28.2	1,595	26.5	2,080
Second crop after deep tillage.	...do....	E-H	432	41.7	1,960	17.7	36.3	1,160	31.9	1,184	26.9	1,511
Ordinary plowing...	...do....	G	720	43.1	2,120	16.6	40.9	1,400	33.5	1,413	28.9	1,660
Deep tillage each year.	Wheat.	N-D	1,456	32.3	2,100	9.8	32.8	1,400	25.0	1,652	......	......
First crop after deep tillage.	...do....	P-C	3,456	37.1	2,760	10.9	26.3	1,480	24.8	2,565	......	......
Second crop after deep tillage.	...do....	O-B	1,904	21.7	2,090	11.2	32.7	1,520	21.9	1,838	......	......
Ordinary plowing...	...do....	Q-A	1,904	29.8	2,810	8.7	34.2	1,040	24.2	1,918	......	......

[a] Where two plots appear under the same heading, the crop is on the first one in the odd years and on the second in the even years.

[b] For three years, 1911, 1913, and 1916, when little or no grain was produced the yield of corn is in total pounds per acre.

[c] Example: Average yield of wheat for deep tillage after both wheat and corn is 13.8+18.6÷2=16.2.

In the four plots where wheat follows corn there is a more pronounced evidence of a positive result. The heaviest yield has been on the ordinary-plowed plot, the next heaviest from the second year after deep tillage, the third heaviest from the first year after deep tillage, and the

lowest yield from the plot deep-tilled every year. This relation has been quite consistent during three of the five years for which results have been obtained. During the two other years little difference as a result of the different preparations is exhibited.

From the corn crop no significant differences as a result of different depths of tillage have been obtained. Between the average of the two plots deep-tilled each year and the average of the two plots ordinary-plowed each year there is as an average of six years' results a difference of only 0.4 bushel of corn in favor of one and 60 pounds of fodder in favor of the other. In the three years when grain was produced both of these averages exceeded those of the plots alternately deep-tilled. In the three years in which fodder only was produced, the yields of these plots exceeded those of one of the alternately deep-tilled plots, but were in turn exceeded by that of the other.

That these differences are accidental rather than due to the effect of the tillage method is shown by the fact that they are determined, in at least a part of the cases, by differences in 1911 in the yield of plots exactly similar in their preparation. The only differences of cultivation or sequence that year were that the four plots F, E, D, and C, being the four which appear under the headings "Deep tillage each year" and "First crop after deep tillage," were deep-tilled, while the other four plots were given ordinary plowing. Two of the deep-tilled plots and two of those shallow-plowed produced some grain, while the other four did not. The yields are given, however, as total weights of fodder. In no other year has there been observed in plots of different treatment such great differences as were evidenced this year between plots of similar treatment.

From the evidence presented by this experiment it is safe to say that at this station deep tillage has no efficacy either in overcoming drouth or in increasing the yields of wheat or corn in the average of a series of years. There is, indeed, strong indication that the yields of wheat may be materially reduced by this practice. The conclusiveness of this evidence is strengthened by its general agreement with the results of the shorter experiment in the use of dynamite and the longer and more extensive experiment with subsoiling.

ARDMORE FIELD STATION

DEEP TILLAGE BY THE USE OF DYNAMITE

The deep tillage with dynamite experiment at Ardmore, S. Dak., is similar to the one at the Judith Basin Field Station, and in every particular except the size of the plots and their grouping in the field is the same as the deep-tillage experiment at Akron. Figure 4 illustrates the manner in which the plots are laid out. In preparation for the crop raised in the odd years the two center tiers of plots running north and south are dynamited. In preparation for the crop raised in the even

years the two center tiers of plots running east and west are dynamited. In the odd years the two north tiers of plots are cropped to wheat and the two south tiers to corn. In the even years the two east tiers of plots are cropped to wheat and the two west tiers are cropped to corn. The size of each plot is ¼ acre.

Eight plots were dynamited late in September, 1912. The charges of powder were placed 15 feet apart in each direction, ½ pound of 20 per cent powder being used in each charge. The charges were fired at a depth of 30 inches, which is as deep as is practicable to place them in this soil when it is dry. The soil on which this experiment is located is of the heaviest clay of the type commonly known as gumbo. Apparently it is almost impervious to water under some conditions, and samples taken to a depth of 10 feet reveal no change in its character. After the explosive had been used, an examination of the soil showed that it had not been in the least affected at a distance greater than 5 feet from the location of the charge. In many cases the soil was not disturbed beyond a distance of 3 feet from the charge. This was when the soil was very dry. When the soil is at all moist, the powder exerts a packing rather than a disrupting effect.

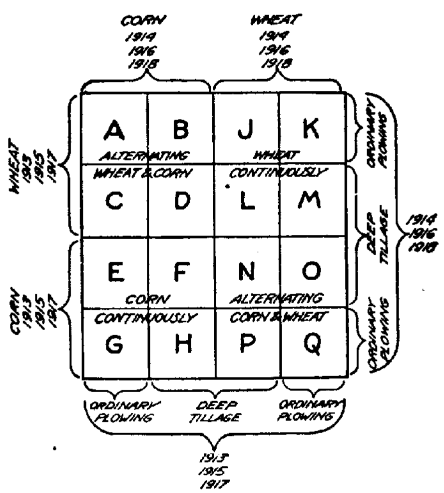

FIG. 4.—Diagram of plots in dynamiting experiment at Ardmore, S. Dak.

After the first year the powder company withdrew its active cooperation, but the experiment has been continued by the Department, and the blasting done each year as provided for in the original outline.

Each fall, after the dynamiting is completed, the entire 16 plots are plowed to a depth of 7 or 8 inches. They are left rough to overwinter, the object being to leave them in condition to catch and retain the maximum amount of snow and rainfall. In the spring the plots are given the necessary tillage with a disk and a harrow to put them in proper conditions for seeding.

In 1913 good stands of both corn and wheat were obtained. This land had produced a crop of sorghum in 1912, and consequently contained no water in storage. The season of 1913 was very dry, particularly during

June, July, and August. The wheat reached a height of only about 10 inches and probably would not have yielded as much as 1 bushel per acre. It was clipped with a mower and raked off the ground, no attempt being made to obtain yields. No appreciable difference could be observed between the plots as a result of the dynamiting. The corn crop suffered badly from drouth and did not ear. It was severely damaged by hail, and the yields were not determined. No appreciable difference could be observed between any of the plots.

In 1914 a very promising crop of wheat was destroyed on June 24 by a heavy hailstorm. The corn suffered from this storm, and again from a second one on July 7. Hail in August again damaged it to a limited extent. During the latter part of the season it suffered from lack of water and was cut for fodder on August 18. No ears were produced. Both 1915 and 1916 were productive of good crops of both wheat and corn.

Table XVII gives the yields from this experiment. They are arranged and averaged the same as the data in Table XVI, which reports the results of the deep-tillage experiment at Akron.

TABLE XVII.—*Yields at Ardmore (S. Dak.) Field Station of wheat and corn in dynamiting experiment for the years 1914 to 1916, inclusive*

Crop and treatment.	Previous crop.	Plot.[a]	Yield (bushels per acre).				
			1914[b]	1915	1916	Average.	Average of similar treatment after both wheat and corn.
WHEAT.							
Dynamite each year	Wheat	L	......	26.9	15.9	21.4	21.0
First crop after dynamite	do	J-M	......	35.3	11.7	23.5	22.2
Second crop after dynamite	do	M-J	......	35.7	18.7	27.2	28.3
Ordinary plowing	do	K	......	31.5	16.1	23.8	23.0
Dynamite each year	Corn	D-N	......	25.7	15.3	20.5	......
First crop after dynamite	do	B-O	......	26.8	14.7	20.8	......
Second crop after dynamite	do	C-P	......	39.8	19.0	29.4	......
Ordinary plowing	do	A-Q	......	26.4	18.0	22.2	......
CORN.							
Dynamite each year	Corn	F	632	17.4	14.7	16.1	18.7
First crop after dynamite	do	H-E	716	40.4	15.6	28.0	26.2
Second crop after dynamite	do	E-H	634	29.4	14.3	21.9	22.6
Ordinary plowing	do	G	824	33.9	22.3	28.1	29.2
Dynamite each year	Wheat	N-D	860	24.1	18.2	21.2	......
First crop after dynamite	do	P-C	672	35.3	13.3	24.3	......
Second crop after dynamite	do	O-B	1,168	28.1	18.2	23.2	......
Ordinary plowing	do	Q-A	1,180	40.6	20.0	30.3	......

[a] Where two plots appear under the same heading, the crop is on the first one in the odd years and on the second in the even years.
[b] Weight of fodder; no grain produced.

With the wheat crop the difference, if any, between dynamiting each year, the first year after dynamiting, and not dynamiting at all appears to be slightly in favor of the latter. The highest yields have been obtained each year both where wheat follows wheat and where wheat follows corn on plots the second year after dynamiting. The fact that these results have been obtained from four separate plots would seem to remove it from the possibility of being due to soil variation. With the corn crop the tendency has been for the land not dynamited at all to produce the highest yields. The second highest average yield has been the first year after dynamiting, the third highest the second year after dynamiting, while the lowest yields have been from those plots dynamited each year.

The results of both crops together indicate that it is very questionable whether any actual increase of yields may be obtained on this soil as a result of dynamiting. There can be no question, however, of the conclusion that there is no chance of yields being increased sufficiently to make the operation a profitable one. The experiment is being continued, however, and has been somewhat extended. In order to determine the effect of a complete loosening of the soil regardless of cost, one one-tenth acre plot was dynamited in the fall of 1915 with charges set close enough together to insure the loosening and stirring of all the soil on the plot, the charges being fired at a depth of 30 inches. In 1916 the appearance and the yield of the wheat on this plot was practically the same as that on an adjoining plot that was ordinary fall-plowed.

BELLEFOURCHE FIELD STATION

DEEP TILLAGE BY THE USE OF DYNAMITE

In October, 1912, a representative of the powder company gave a demonstration in blasting soil for field crops at the Bellefourche Field Station. A one-tenth acre plot (plot 1 in Series VIII, field B), 8 rods by 2 rods, that had been in millet (*Panicum miliaceum*) was selected for the demonstration. The shots were placed 20 feet apart each way and 3 feet deep. This plot and two adjoining plots that were used for controls had been plowed shortly before the dynamiting. The control plots (plots 1 in Series VII and Series IX) adjoined the ends of the dynamited plots, one on the east and one on the west. The soil on the plots in Series VII and VIII is uniform, but that on the plot in Series IX is poorer on account of a hardpan spot covering nearly half its area. This plot was manured.

In the spring of 1913 all three plots were treated alike and seeded to Sixty-Day oats. The dynamiting and manuring were not repeated but the plots were given uniform treatment and again seeded to oats in 1914. Both seasons spring conditions were favorable, but after the latter part of June or the first part of July the crop suffered from drouth.

In 1915 all the plots were given the same treatment and seeded to wheat, for which the season proved extraordinarily favorable. The plots were all fallowed in 1916 and seeded to alfalfa in 1917. The yields for the three years following the dynamiting are shown in Table XVIII.

TABLE XVIII.—*Yields at Bellefourche (S. Dak.) Field Station of oats and wheat in dynamiting experiment for the years 1913, 1914, and 1915*

Plot No.	Treatment.	Yield in bushels each year.		
		1913, oats.	1914, oats.	1915, wheat.
B VII-1	Fall-plowed	25.9	19.1	58.8
B VIII-1	Fall-plowed and dynamited	18.4	18.8	54.0
B IX-1	Fall-plowed and manured	24.1	16.1	52.8

The only conclusion that can be drawn from these yields is that dynamiting is not effective in increasing yields. The first year after dynamiting the effect appears to have been quite the opposite. It is impossible to say how much effect the manure used on Plot IX-1 had in overcoming the initially poor condition of that plot.

JUDITH BASIN FIELD STATION

DEEP TILLAGE BY THE USE OF DYNAMITE

An experiment similar to those at Akron and Ardmore, in the use of dynamite as a medium of deep tillage was inaugurated in the fall of 1912 at the Judith Basin Field Station. The plots are ¼ acre in size. The plan of the experiment is identical with that at Ardmore, as shown in figure 4 and described in connection with the results from that station.

The land on which this experiment was started was prairie sod broken in June, 1909, and seeded to winter wheat late in November of that year. A poor crop of wheat was harvested from the land in 1910, the yield being 10 bushels per acre. The land was plowed in the spring of 1911 and seeded to flax, which yielded 12 bushels per acre. The Judith Basin Field Station obtained possession of this tract of land in November, 1911. The field was bare -fallowed during 1912, being plowed late in June, and double-disked and harrowed three times during the remainder of the season. The plots were staked out, and the first dynamiting was done in September of that year. The entire block of 16 plots was plowed in the spring of 1913 and seeded to wheat and corn, as called for in the outline of the experiment. Very little difference could be noted in the growth of grain on the different plots during the season. At harvest time the plots were as uniform in growth and height as if they had all received the same treatment.

In preparation for the crop of 1914 dynamiting was done in the fall, but all plowing was deferred until spring. Good stands were obtained with both wheat and corn and good crops produced.

In preparation for the crop of 1915 the dynamiting was again done in the fall and the plowing in the spring. In preparing for the crop of 1916 both dynamiting and plowing were done in the fall. The plowing remained rough over the winter. In the spring all plots were double-disked and harrowed in preparation for seeding. As in previous years, no variation in growth that could be attributed to the use of dynamite could be observed in the plots in the field.

The yields from the 16 plots in this experiment for the four years 1913 to 1916, inclusive, are presented in Table XIX. The arrangement of the data in this table is the same as in Tables XVI and XVII. The yields of corn are given in total pounds of fodder per acre. The corn used in these experiments is raised for fodder at this station and no grain produced.

TABLE XIX.—*Yields at Judith Basin Field Station of wheat and corn in dynamiting experiment for the years 1913 to 1916, inclusive*

Crop and treatment.	Previous crop.	Plot.[a]	Yield.					Average of similar treatment after both wheat and corn.
			1913	1914	1915	1916	Average.	
WHEAT.								
Dynamite each year	Wheat.	L	31.1	20.2	30.6	18.8	25.2	26.2
First crop after dynamite.	...do...	J–M	33.2	18.6	32.1	19.7	25.9	26.4
Second crop after dynamite.	...do...	M–J	30.8	17.3	29.8	19.4	24.3	25.9
Ordinary plowing	...do...	K	30.6	17.0	30.1	17.1	23.7	23.4
Dynamite each year	Corn...	D–N	31.2	20.6	32.6	24.0	27.1	......
First crop after dynamite.	...do...	B–O	31.2	20.1	32.1	23.7	26.8	......
Second crop after dynamite.	...do...	C–P	27.9	23.2	32.3	26.4	27.5	......
Ordinary plowing	...do...	A–Q	26.7	17.3	27.9	20.6	23.1	......
CORN.[b]								
Dynamite each year	Corn...	F	2,640	9,700	2,115	4,400	4,714	3,903
First crop after dynamite.	...do...	H–E	2,240	8,500	2,120	3,400	4,065	3,309
Second crop after dynamite.	...do...	E–H	2,880	8,700	1,695	4,600	4,469	3,998
Ordinary plowing	...do...	G	2,200	8,400	1,840	4,400	4,210	3,363
Dynamite each year	Wheat.	N–D	2,580	5,700	1,685	2,400	3,091	......
First crop after dynamite.	...do...	P–C	2,480	3,400	1,530	2,800	2,553	......
Second crop after dynamite.	...do...	O–B	2,440	6,900	2,165	2,600	3,526	......
Ordinary plowing	...do...	Q–A	1,880	3,900	1,480	2,800	2,515	......

[a] Where two plots appear under the same heading, the crop is on the first one in the odd years and on the second in the even years.

[b] Yields of corn in pounds of fodder. No grain produced.

In the results from the wheat crop no difference is exhibited between the yields from the plots dynamited each year and from those plots dynamited every other year either where wheat follows wheat or where wheat follows corn. All of these apparently have an advantage of about 3 bushels per acre over the plots not dynamited at all.

The yields from the corn crop exhibit a marked effect as a result of crop sequence, the average yield following corn being nearly ¾ ton per acre greater than the average yield following wheat. Every plot following corn has outyielded every plot following wheat. No such marked effect or consistency of results is to be noted as a result of dynamiting. The yield of the plot dynamited each year has been practically the same as the yield the second year after dynamiting on the plot alternately dynamited and not dynamited. Both of these yields have been about 600 pounds per acre greater than those from the plot not dynamited at all and from the first year after dynamiting on the plot alternately dynamited and not dynamited. This inconsistent combination of results indicates very strongly that the variations are accidental rather than due to the effects of dynamiting.

Granting the proposition, which is by no means conclusively proved by the data at hand, that yields may be slightly increased by the use of dynamite, the possible increase is too small to hold out any hope of the operation being profitable even if the effect of the dynamite persisted for a considerable number of years.

SUMMARY OF RESULTS OF DEEP TILLAGE BY THE USE OF DYNAMITE OR SPECIAL PLOWS

In summation of the results from all stations it seems very questionable that deep tillage either by the use of special plows or dynamite has been effective in increasing yields. The most favorable evidence is with corn the second year after dynamiting at Akron; with wheat the second year after dynamiting at Ardmore; and with wheat after dynamiting at Judith Basin. The apparent increases in these cases are small and are offset by losses so that the averages of all trials with both crops show no increases over ordinary plowing.

Deep tilling by these methods, as well as by subsoiling, has been of no value in overcoming drouth.

The results offer no hope of profitably increasing the yield of either wheat or corn by means of deep tillage.[1]

RESULTS OF OTHER INVESTIGATIONS OF SUBSOILING AND DEEP TILLING

UTAH.—Experimental work has been conducted cooperatively at the Nephi, Utah, Substation since 1907 by the Office of Cereal Investigations of the Bureau of Plant Industry and the Utah Agricultural Experiment Station.

[1] These conclusions are supported and strengthened by the results of 1917, which was a year of low yields owing to drouth.

Cardon (1) summarizes the results of five years' work with deep tillage for winter wheat as follows:

The results of five years show that there was no advantage in deep plowing or subsoiling over shallow plowing so far as moisture conservation is concerned. There was no material difference in the yields obtained from plats plowed at different depths, varying from 5 to 18 inches. The highest average yield was obtained from plats plowed 10 inches deep, and the lowest average yield was from the plats subsoiled 18 inches deep, while the 5-inch plowing yielded higher than the 15-inch subsoiling.

ILLINOIS.—Mosier and Gustafson (4) report the results of investigations in Illinois as follows:

Investigations to determine the value of subsoiling in preparation for corn on gray silt loam on tight clay, the common prairie soil of the lower Illinois glaciation, have been carried on for eight years at the Odin Field, in southern Illinois. * * * With every soil treatment there was an almost uniform decrease in yield for subsoiling. The general average for eight years shows a decrease of 2.7 bushels per acre. The alleged benefit of subsoiling is the increasing of the water capacity of soils and of their ability to retain water during dry seasons. Yet in 1913 and 1914, both of which were very dry seasons, this method, as a general average, gave only the very slight increase of .5 and .7 bushels respectively. The subsoil was loosened by the plow, but ran together as soon as it was wet and became approximately as it was before. The experiments as a whole show that subsoiling on this type of soil not only does not pay, but is a losing operation, for in order to pay for the extra work involved in subsoiling, at least a three-bushel increase would be necessary.

Under the head of "Deep tilling" in the same bulletin the authors present no data of yield, but make the following statement:

Farmers are frequently urged to purchase a machine for plowing to a depth of 12 to 15 inches. There is little doubt that under certain conditions of soil and climate such plowing would be beneficial; but the results obtained by the Experiment Station in this state with the deep-tilling machine on the common prairie soil of the corn belt do not warrant recommending its purchase.

PENNSYLVANIA.—Noll (5) summarizes the result of three years' trial of the Spalding deep-tillage machine on the farm of the Pennsylvania State College as follows:

The soil in which this experiment was conducted is of the Hagerstown series. It varies in texture from clay loam to gravelly silt loam, but is chiefly clay loam. The surface soil is so deep that in most of the area little of the clayey subsoil was turned up. The soil is well drained.

Eight plats 35.5 ft. wide, varying in length from 902.5 ft. to 1,000 ft. were plowed at first. These were later made 957.2 ft. long and comprised .78 of an acre each.

Timothy sod was plowed for corn in the fall of 1909 and the spring of 1910, two plats being plowed with each implement in the fall and two in the spring.

In the fall of 1910 and the spring of 1911 the corn stubble land was plowed in the same way, and in the spring four plats were seeded to oats and four to beardless barley and alfalfa.

In the fall of 1911 the four plats which had received oats were plowed and seeded to wheat, two plats being plowed with each implement.

The crops for which the plowing was done were corn, oats, barley, wheat, and alfalfa, each one year.

Under the conditions named above the two kinds of plowing gave practically the same results for all the crops grown.

MISSISSIPPI.—Ricks (*6*), reporting the results of subsoiling with plow and with dynamite at the Central Mississippi Station, shows the following corn yields:

In 1913, not subsoiled, 31.8 bushels; subsoiled with plow, 25.5 bushels; subsoiled with dynamite, 27.7 bushels. In 1914 the yields were: Not subsoiled, 30 bushels; subsoiled with plow, 27.2 bushels; subsoiled with dynamite, 29.1 bushels. He says:

These plats were on a Houston clay soil of medium fertility. The subsoiling was done in March of 1913. The check plats were broken about seven inches deep. . . . . Subsoiling for corn, as well as for any other crop gives us no returns.

The same author (7) in describing the preparation of the soil for alfalfa says:

Good deep plowing where there is good drainage has given us as satisfactory results as subsoiling with dynamite or with a subsoil plow.

This is under an annual rainfall of about 60 inches.

TEXAS.—Hastings and Letteer (*2*) in reporting on the experiments in subsoiling at San Antonio, Tex., covering three years, 1910, 1911, and 1912, conclude that—

(1) Subsoiling is an expensive practice and so adds to the cost of preparation for a crop that unless materially increased yields result it can not be profitably adopted as a regular farm practice.

(2) Subsoiling has been tested at the San Antonio Experiment Farm for three years in rotation experiments with corn, cotton, and oats for hay and for grain.

(3) The yields of corn, cotton, and oats for hay and for grain have been either slightly increased or slightly decreased on subsoiled land. In no instance has the difference been significant.

(4) The depressing residual effect of subsoiling on the yields of corn and cotton was most marked when the crop was planted from 1 to 8 months after subsoiling; 15 months after subsoiling but little depressing effect was noted.

(5) In the soil-moisture studies so far made at San Antonio it has been found that subsoiling has not increased the moisture content of the soil.

(6) The results of these tests indicate that since neither the moisture content of the soil nor the yields of corn, cotton, and oats are increased by subsoiling, the practice is not advisable in connection with the crops mentioned in the San Antonio region of Texas.

RUSSIA.—Rotmistrov (*8*), in discussing the state of the drouth question, says:

Deep mellowing of the soil which all the writers on this subject unanimously regard as a matter of great importance with regard to fighting against drouth, has also very little real significance. On the Odessa field there have been more than 1,000 experiments made on the effect of deep plowing for winter and spring crops, and no difference in favor of deep [10½ inches] or even mediate [7 inches] plowing was obtained in the harvest. Investigations into the humidity of the soil also showed no difference in that respect between deep and shallow [3½ inches] plowing.

The argument in favor of deep plowing, that deeply mellowed soil imbibes more atmospheric residue [precipitation], falls through, because little residue settles on the steppes districts and it all enters the soil whether deeply plowed or not. On certain types of soil and in more northern regions deep plowing may have a beneficial effect for other reasons—airing the soil, etc.—but not as regards opposing drouth. [TRANSLATION.]

SUMMARY

Subsoiling, deep tilling, and soil dynamiting are all operations that increase the expense of production over that on ordinary plowing. They also increase the amount of labor expended on a given area, or reduce the acreage that can be prepared by a given working unit. Subsoiling is as laborious and expensive an operation as plowing, but must be done in addition to it and at the same time. Plowing with a special deep-tillage machine to a depth of 12 to 14 inches requires considerably more than double the labor, time, and expense of ordinary plowing. The use of dynamite in the least quantity that might be effective involves an added expense for material and labor of more than $20 per acre. Consequently, in order to justify their use, these practices should show increases in yields sufficient to pay for the extra expense involved.

In any year a combination of conditions favorable to subsoiling may occur at any station. At some stations the average results of a series of years shows no measurable effect on crop yields as a result of subsoiling. At other stations the effect has clearly been to decrease yields. At still other stations, particularly at Hays, Kans., subsoiling appears to have resulted in significant increases in crop yields. With some of the crops showing increases, however, the yields from either method have been too small to be profitable.

Recognizing the fact that there may be times and places giving results favorable to subsoiling or other methods of deep tilling, the average yields obtained in the extensive experiments here reported seem to warrant the conclusion that as a general practice for the Great Plains as a whole no increase of yields or amelioration of conditions can be expected from the practice.

In their relative response to deep tillage there is no marked difference to be observed between crops.

Subsoiling and deep tilling have been of no value in overcoming drouth. The effect, on the contrary, apparently has been to reduce the yields in those seasons that are below the average in production.

Experiments have been conducted with the subsoil plow, the Spalding deep-tillage machine, and dynamite. The effect or lack of effect of deep tillage appears to be essentially the same, irrespective of the means by which it is accomplished.

These conclusions are the result of extensive experiments covering a wide range of crops, soils, and conditions in the Great Plains. Experiments conducted in the Great Basin under semiarid conditions with the greater part of the precipitation occurring in the winter; under humid conditions in the States of Illinois, Pennsylvania, amd Mississippi; under semiarid conditions at San Antonio, Tex.; and under semiarid conditions on the black soil of southern Russia have all led to the same con-

clusion: that yields can not be increased nor the effects of drouth mitigated by tillage below the depth of ordinary plowing.

The quite general popular belief in the efficiency of deep tillage as a means of overcoming drouth or of increasing yields has little foundation of fact, but is based on misconceptions and lack of knowledge of the form and extent of the root systems of plants and of the behavior and movement of water in the soil.

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OVERWINTERING OF THE CITRUS-CANKER ORGANISM IN THE BARK TISSUE OF HARDY CITRUS HYBRIDS [1]

COOPERATIVE INVESTIGATIONS BETWEEN THE DEPARTMENT OF PLANT PATHOLOGY, ALABAMA AGRICULTURAL EXPERIMENT STATION, AND THE OFFICE OF CROP PHYSIOLOGY AND BREEDING INVESTIGATIONS, BUREAU OF PLANT INDUSTRY, UNITED STATES DEPARTMENT OF AGRICULTURE

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During the course of our field inoculation experiments conducted in southern Alabama in the fall of 1917 to determine the resistance and susceptibility to Citrus-canker of some of the wild relatives, Citrus fruits, and the more common hybrids of the genus Citrus, a most interesting feature has recently developed in connection with the ability of the organism to survive the winter in the outer bark tissue of some of these plants.

All the plants were set in the isolation field in July, 1917, extreme precautions surrounding the experiments being maintained. By the middle of September they had made a rapid growth and were at that time in fine shape for inoculation.

Included in a series of inoculations made on September 16, 1917, were the hybrids Rusk citrange (CPB 7956A),[2] Savage citrange (CPB 7961), and citrandarin (CPB 40175A), and two plants each of *Poncirus trifoliata*, grapefruit (*Citrus grandis*), and Satsuma orange (*Citrus nobilis* var. *unshiu*. In making the inoculations 100 cc. of a 48-hour culture of *Pseudomonas citri* in beef bouillon were thoroughly sprayed on each plant by means of an atomizer.

Although repeated observations were made during October and November of the plants enumerated above, only *P. trifoliata* and grapefruit showed any evidence of canker infection, and this only occurred to a slight extent on the foliage. It was thought that absence of infection on the Rusk and Savage citranges, as well as on the citrandarin and other plants, could be in part accounted for by the unfavorable temperature prevailing at the time the inoculations were made. This view was also somewhat strengthened by the fact that the more susceptible plants, such as grapefruit and *P. trifoliata* revealed only a minimum amount of infection two months after making the inoculations. With such unfavorable temperatures prevailing because of the lateness of the season no positive results were obtained with the hybrids, particularly with the citranges and citrandarins.

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[1] Published with the approval of the Director of the Alabama Agricultural Experiment Station.

[2] CPB—Crop Physiology and Breeding Investigations.

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Notwithstanding the fact that all the plants were carefully observed at intervals throughout the winter, no infection was found on the hybrids, although these were in a thrifty condition, with an abundance of healthy foliage.

On April 2, 1918, positive evidence of Citrus-canker infection was observed on the Rusk and Savage citranges, as well as on the citrandarin. The plants of *P. trifoliata* (Pl. 58, B) that were inoculated at the same time (September 16, 1917) also revealed new infections. Unfortunately the grapefruit and Satsuma plants were killed by the low temperatures prevailing during the winter months, and no further data could be obtained here. The hybrid plants were heavily infected, the infection in each case being confined to the main stem and branches (Pl. 58, A, C, D). The infection appeared simultaneously and extensively on all the twigs, branches, and main stems of the plants. Although the foliage was very healthy and apparently active and had been so throughout the winter, no sign of infection was observed on the leaves.

Cankered twigs from the Rusk and Savage citranges, the citrandarin, and *C. trifoliata* were collected and taken to the laboratory to ascertain whether the organism was viable and could be recovered in culture. Within four days good colonies of the organism appeared on the plates, which left no question of their viability.

From the data at hand it would appear that the Citrus-canker organism is able to withstand the winter within the outer-bark tissues of the host. Wolf[1] states that the lenticels probably serve as portals of entrance for the organism into the stems, and from the results it would appear that this view is entirely possible. The organism probably gains entrance into the outer-bark tissue through the lenticels and remains dormant through the winter months. On the return of more favorable conditions of temperature, humidity, and rapid growth of the plant, the canker organism becomes active.

The weather records in this vicinity during the fall and winter of 1917–18 reveal a minimum temperature of 15.5° F. It would seem, therefore, that the bacteria which gained entrance into the outer-bark tissues, probably through the lenticels, at the time of inoculations, September 16, 1917, were offered sufficient protection to withstand the above temperature, whereas the foliage infections were completely killed or their virulency lowered to such an extent that infection was not possible.

From the fact that the Citrus-canker organism is able to withstand such a low temperature and remain in a dormant condition for 6½ months in the outer-bark tissues of the twigs and branches, extreme care and caution must be exercised in the use of Citrus plants from canker-infected regions in the selection of budwood from nurseries and orchards in which canker has been found within a year, in the length of the quarantine period, and in the complete eradication of Citrus-canker from nurseries and orchards, especially in plantings of *P. trifoliata.*

[1] WOLF, F. A. CITRUS-CANKER. *In* Jour. Agr. Research, v. 6, no. 2, p. 79. 1916.


A
B
C
D

PLATE 58

Citrus-canker spots on twigs from plants in the isolation field, inoculated on September 16, 1917. These first appeared on April 2, 1918. Photographed on May 2, 1918.

A.—Citrandarin (CPB 40175A).

B.—*Poncirus trifoliata* (seedling, Alabama).

C.—Savage citrange (CPB 7961).

D.—Rusk citrange (CPB 7956A).